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THE RADIATION AND HEAT BUDGET OF THE MINTZ-ARAKAWA MODEL: JANUARY

Anne D. Kahle, et al

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10. ABSTRACT

Comparison of the radiation and heat budgets of the Rand general circulation model for a January simulation with observational and theoretical values. In the model too much solar radiation is absorbed at the earth's surface due primarily to insufficient atmospheric absorption and reflection. In the tropical latitudes the long-wave flux divergences over the atmospheric column appear to be too large. In the mid-latitudes of both hemispheres these values are in better agreement, while at higher latitudes they again diverge from comparable values. Since the solar flux reaching the surface and the long-wave fluxes are dependent on cloudiness, moisture, and temperature, it is not evident that the fault lies necessarily in the radiative portions of the model. While the heat budget calculations seem reasonable compared to other investigations, our components are generally the largest. This is probably related to the fact that the model possesses a vigorous general circulation.

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Anne B. Kahle and Frank Haurwitz

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PREFACE

This report describes the results of a detailed examination of the radiation and heat budgets of the Rand version of the Mintz-Arakawa two-level atmospheric general circulation model for a January control run. The Mintz-Arakawa model is used extensively in the Rand Climate Dynamics Project, for the Defense Advanced Research Projects Agency, and this study represents part of the continuing effort to verify and improve the model. Considerations of the sort undertaken here are necessary to insure that the radiation and heat terms in the model are good approximations to the real atmosphere, and that we may reasonably perform numerical experiments with the model. In addition, this work provides us with reference levels for the analysis of such experiments. (A similar report dealing with the July radiation and heat budget is planned.)

Reports related to this study include the following: C. Schutz and W. L. Gates, *Global Climatic Data for Surface, 800 mb, 400 mb: January*, R-915-ARPA, November 1971; W. L. Gates, E. S. Batten, A. B. Kahle, and A. B. Nelson, *A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model*, R-877-ARPA, December 1971; C. Schutz and W. L. Gates, *Supplemental Global Climatic Data: January*, R-915/1-ARPA, May 1972; W. L. Gates, *The January Global Climate Simulated by the Two-Level Mintz-Arakawa Model: A Comparison with Observation*, R-1005-ARPA, November 1972; W. L. Gates, *The January and July Climates Simulated by a Global 2-Level General Circulation Model: A New Comparison with Observation*, 1973 (in preparation); Staff, Climate Dynamics Project, *The Rand General Circulation Model*, 1973 (in preparation).

SUMMARY

The radiative terms and heat budget in the Rand version of the Mintz-Arakawa two-layer atmospheric general circulation model are examined and compared with the available values from observational and theoretical studies. The absorption, reflection, and scattering experienced by the solar radiation in the atmosphere and at the earth's surface, the long-wave radiative fluxes at the top and bottom of the model atmosphere, the nonradiative transfer of heat via sensible heat and evaporation and condensation, and the planetary albedo are discussed and utilized in deriving the heat budgets across the boundaries of the model and for the atmospheric column and the earth-atmosphere system. In addition, the horizontal transports of heat necessary to balance these budgets are derived. These considerations are all limited to zonal and global results for January from a control integration of the model.

The model indicates that too much solar radiation reaches and is absorbed at the surface due primarily to insufficient absorption in the atmosphere and, in a few areas, insufficient reflection. As for the long-wave fluxes, in the tropical latitudes the flux divergences over the atmospheric column (the difference between the net flux at the surface and the net flux at the top of the atmosphere) appear to be too large. In the mid-latitudes of both hemispheres the values are in better agreement with comparable values, while at higher latitudes they again diverge. It should be noted, however, that since both the flux of solar radiation reaching the surface and the long-wave fluxes are strongly dependent on the distribution of cloudiness, moisture, and temperature, which still need improvement, it is not evident that the fault lies necessarily in the radiative portions of the model.

The various components of the heat-budget calculations seem reasonable when compared with those of other investigators. The globally averaged values of the horizontal heat transport do not go to zero, however, and certain adjustments to the model are suggested. The Mintz-Arakawa heat-budget components are generally the largest discussed, suggesting that the model possesses a rather vigorous general circulation.

In general, the various comparisons between the results of the Mintz-Arakawa model and those of other studies indicate that the model is realistic. Certain modifications are suggested as being immediately practical, while other improvements are seen to depend on improvement of the primary meteorological parameters upon which the radiation calculations are based.

ACKNOWLEDGMENTS

We would like to thank E. S. Batten for many helpful discussions regarding the model and its output and W. L. Gates and M. E. Schlesinger for their thoughtful review of the manuscript. We would also like to thank Patricia Tompkins for the careful preparation and plotting of many of the figures.

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I. INTRODUCTION

This report describes a detailed examination of the radiative terms and heat budget in the Rand version of the Mintz-Arakawa two-layer atmospheric general circulation model. Such a study was undertaken in order to identify what areas of the radiation modeling need improvement. In addition, a preliminary attempt has been made to ascertain why these areas are weak. As part of Rand's program in climate dynamics, this radiation study will be used as a reference or control in the analysis of future experiments on the mechanisms of climate change.

In this report the radiative-energy terms as calculated from control experiment 14 for January will be described. In addition, so that the entire heat budget may be examined, the latent and sensible heat-flux terms will also be considered. In this version of the model the criteria for determining cloudiness have been changed, January rather than mean annual sea-surface temperatures used, and several minor errors removed (Gates et al., 1971; Staff, Climate Dynamics Project, 1973). We will compare the results with a representative sample of observational and theoretical studies. Included will be studies which are primarily concerned with the radiative-energy budgets and therefore utilize climatological values for the relevant meteorological parameters, and also general circulation models which generate their own values for these parameters as well as the radiative quantities. This work complements the studies of the observed January climate (Schutz and Gates, 1971, 1972), the simulated climate for January using an earlier version of the model (Gates, 1972), and an extensive review of the January climate simulated by this newer version of the control experiment (Gates, 1973).

As used here, January refers to the 30-day period from December 31 to January 29. Except in a few cases where data were saved only every six hours, the January averages are based on numbers calculated every half hour. In particular, all the energy terms involved in the heat-budget calculations used in this report are based on half-hour values.

Since some of the studies available for comparison only dealt with seasonal averages, we have found it necessary in those cases to compare our January values with average values for the period from December through February. We have confined our study to zonal and global averages. (A subsequent report will deal with the July and annual radiation budgets.)

In order to proceed with this investigation of the January radiation and heat budget produced by the Mintz-Arakawa model, it is necessary to look first at the distributions of cloudiness, water vapor, temperature, evaporation, precipitation, sensible heat, and surface albedo as generated or used by the model. The examination of these parameters is only of secondary importance to this study; as already mentioned, a more extensive review of these parameters from a perspective not limited just to the radiative and heat budgets is under way and will be reported on elsewhere by Gates. The distributions of these quantities, which are present here for the purpose of comparison, will generally be referenced to the radiation studies in which they were used rather than to their original sources. This initial discussion is followed by an examination of the solar and long-wave radiation terms available from the model. Finally, the radiative and nonradiative components of the heat budget are considered. Zonally averaged values of all these quantities, as derived from the Mintz-Arakawa model, are given in the Appendix.

II. METEOROLOGY

One of the most important meteorological parameters in the model as far as radiation is concerned is the cloudiness. In an earlier version of the model the cloudiness was much too low, permitting too much solar radiation to reach and be absorbed by the surface of the earth (Gates, 1972) and too much long-wave radiation to escape to space. The criteria for determining cloudiness have been revised by Koenig (see Staff, Climate Dynamics Project, 1973) and the cloud amounts are now significantly improved. The zonal average of the total cloudiness from the Mintz-Arakawa model is shown in Fig. 1 (see also Gates, 1973).* Values of cloudiness given by London (1957), Katayama (1967), van Loon (1972), and the data both of ETAC (1971) and of Miller (1970) as presented by Schutz and Gates (1971), are also shown. London's and Katayama's climatological values were prepared for their radiation studies, and the others as parts of climate studies. Haurwitz (1972) and Sasamori et al. (1972) both used van Loon's cloud data for their radiative studies. While the Mintz-Arakawa cloudiness still appears to be too small on a global basis, the low values in the tropics correspond rather well with the recent Tiros satellite data of Miller, which show considerably less cloud cover in those latitudes than do most of the previous estimates. In the higher northern latitudes the various distributions of cloudiness vary rather consistently with latitude, with the Mintz-Arakawa model having slightly less cover than most of the others. The agreement between the data sets in the southern hemisphere is much poorer. This is particularly true south of 50°S, where the Mintz-Arakawa cover is smallest and each distribution shows a different trend with increasing latitude. The effect of cloud distribution on the radiation is quite noticeable and will be discussed below.

The radiation is also affected by the water present in the atmosphere. Zonally averaged precipitable water amounts, compiled by Starr et al. (1957) as part of a climatological study, are given in Fig. 2. The distributions used by the radiative studies of London (1957),

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*In all the figures the values generated by the general circulation models are denoted by a double asterisk, while values generated by the radiation models are denoted by a single asterisk. Climatologically derived values are unmarked.

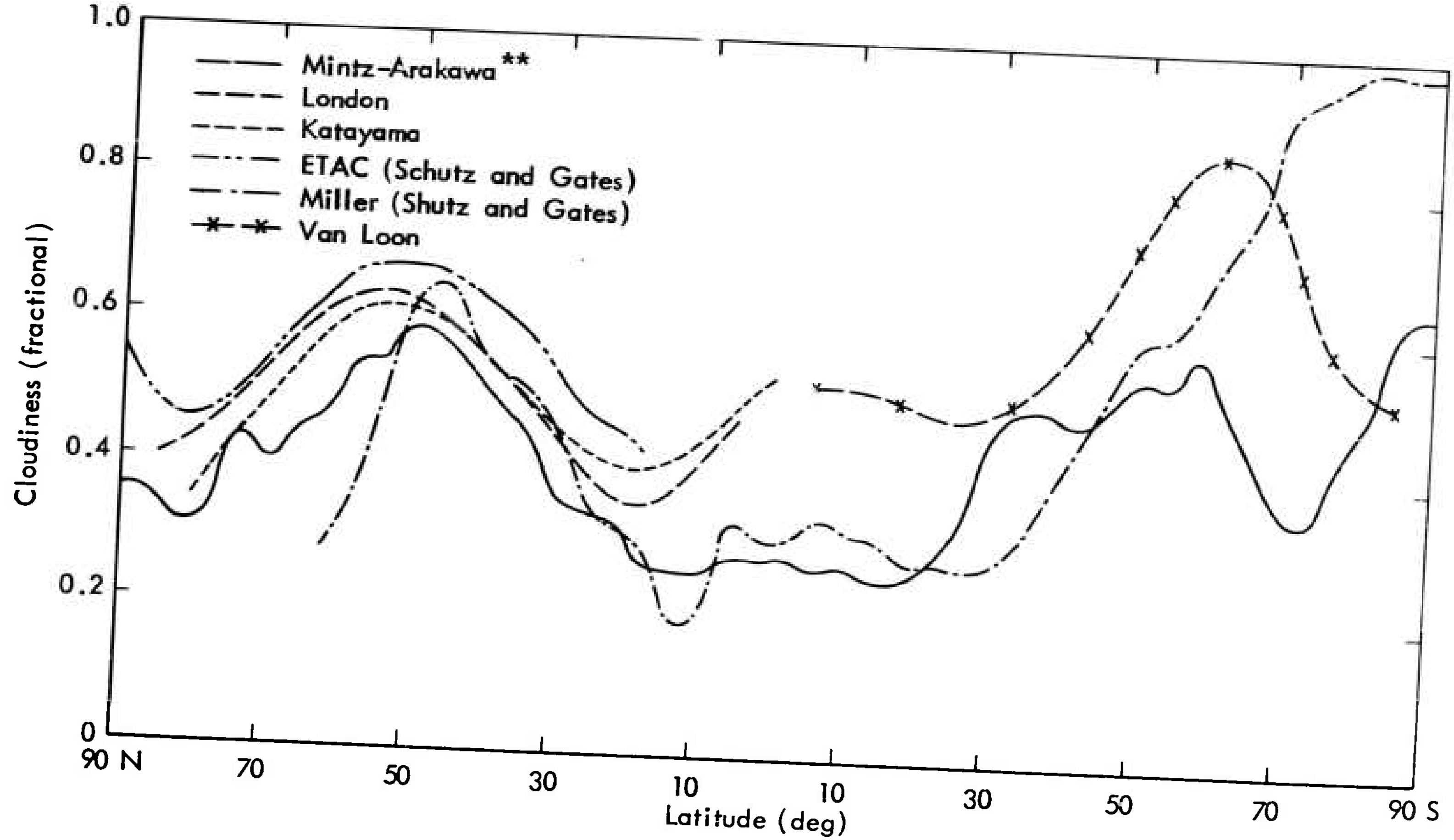

Fig. 1-The zonally averaged total cloud cover.

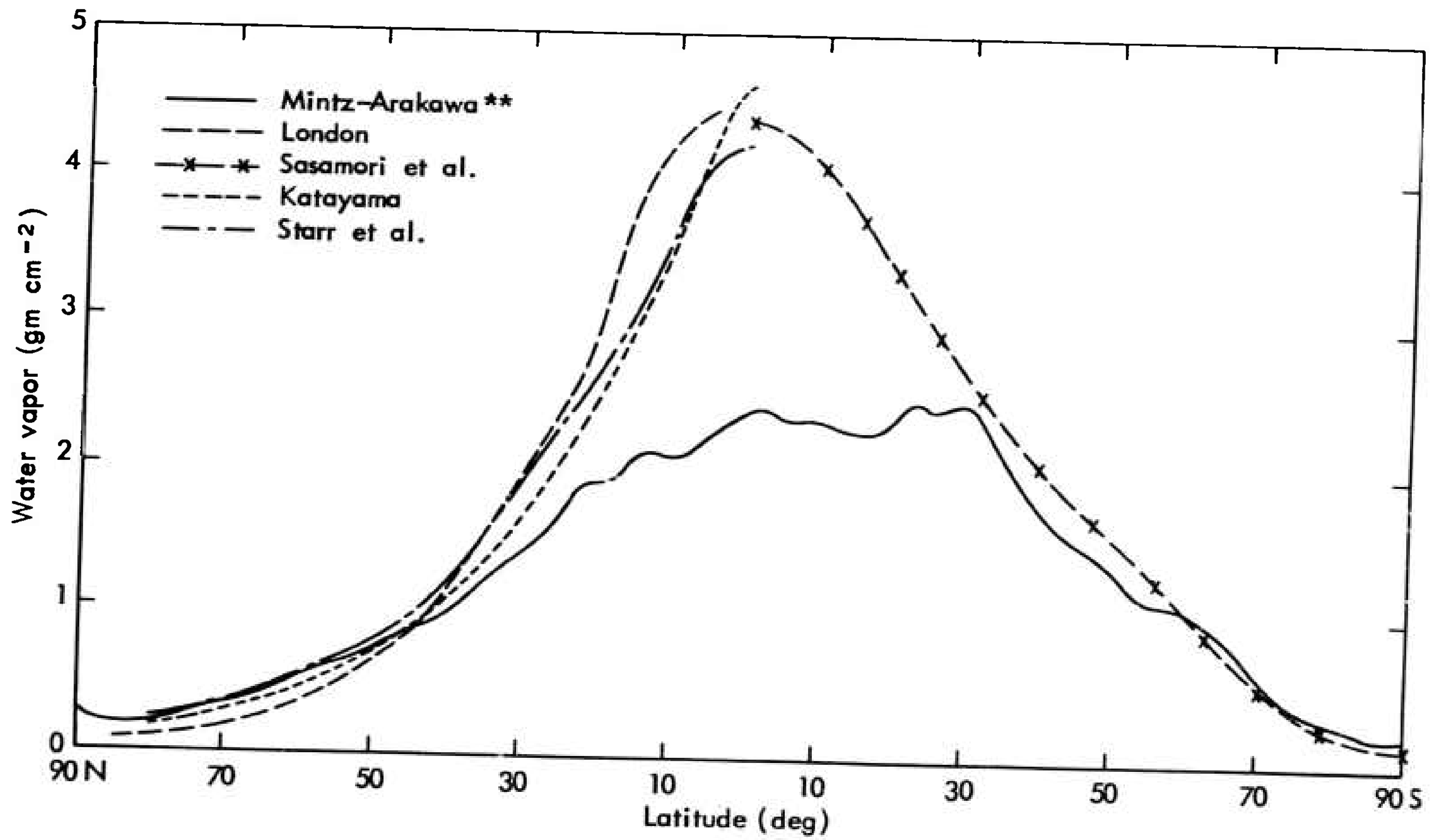

Fig. 2-The zonally averaged precipitable water vapor.

Katayama (1967), and Sasamori et al. (1972) are also presented in Fig. 2. Haurwitz (1972) used essentially the same distribution as that by Sasamori et al. Rather than generating their own values, Holloway and Manabe (1971) used Telegadas and London's (1954) values for the lower troposphere and Murgatroyd's (1960) for the upper troposphere. In the tropics the values generated by the Mintz-Arakawa model differ substantially from the other values, which are all in relatively close agreement. The hydrological cycle is, indeed, felt to be one of the weakest areas of the model, and work is under way to improve it.

The temperature of the atmosphere is important in both the long-wave radiative calculations and the energy conversions involving moisture. Figure 3 compares the January zonally averaged global ground temperatures generated by the Mintz-Arakawa model with the climatological surface-air values collected by Schutz and Gates (1971) from Crutcher and Meserve (1970) for the northern hemisphere and from Taljaard et al. (1969) for the southern hemisphere. The latter values were used by Sasamori et al. (1972) and Haurwitz (1972) in their studies. Also included are the climatological surface-air values prepared by London (1957) for his heat-balance study of the northern hemisphere. The distributions are similar in the tropical and middle latitudes. However at higher latitudes the model generates excessively high temperatures. In the Antarctic this is probably due to an albedo error. While this was corrected prior to the January simulation, residual effects are still noted.

The surface albedo of the model is shown in Fig. 4, along with the albedos given by Katayama (1967) and Sasamori et al. (1972). The albedo used in the Mintz-Arakawa model is based on the mean surface albedo for January of Posey and Clapp (1964) as tabulated by Schutz and Gates (1971), while the albedo of Sasamori et al. is based on the work of Landsberg et al. (1965) and Budyko (1963). There seems to be fairly good agreement among the various data.

The zonally averaged evaporation rates for January, as derived by the general circulation models of Mintz-Arakawa and Holloway and Manabe (1971) and as collected by Budyko (1963) and presented by Schutz and Gates (1971), are given in Fig. 5. Figure 6 presents the precipitation

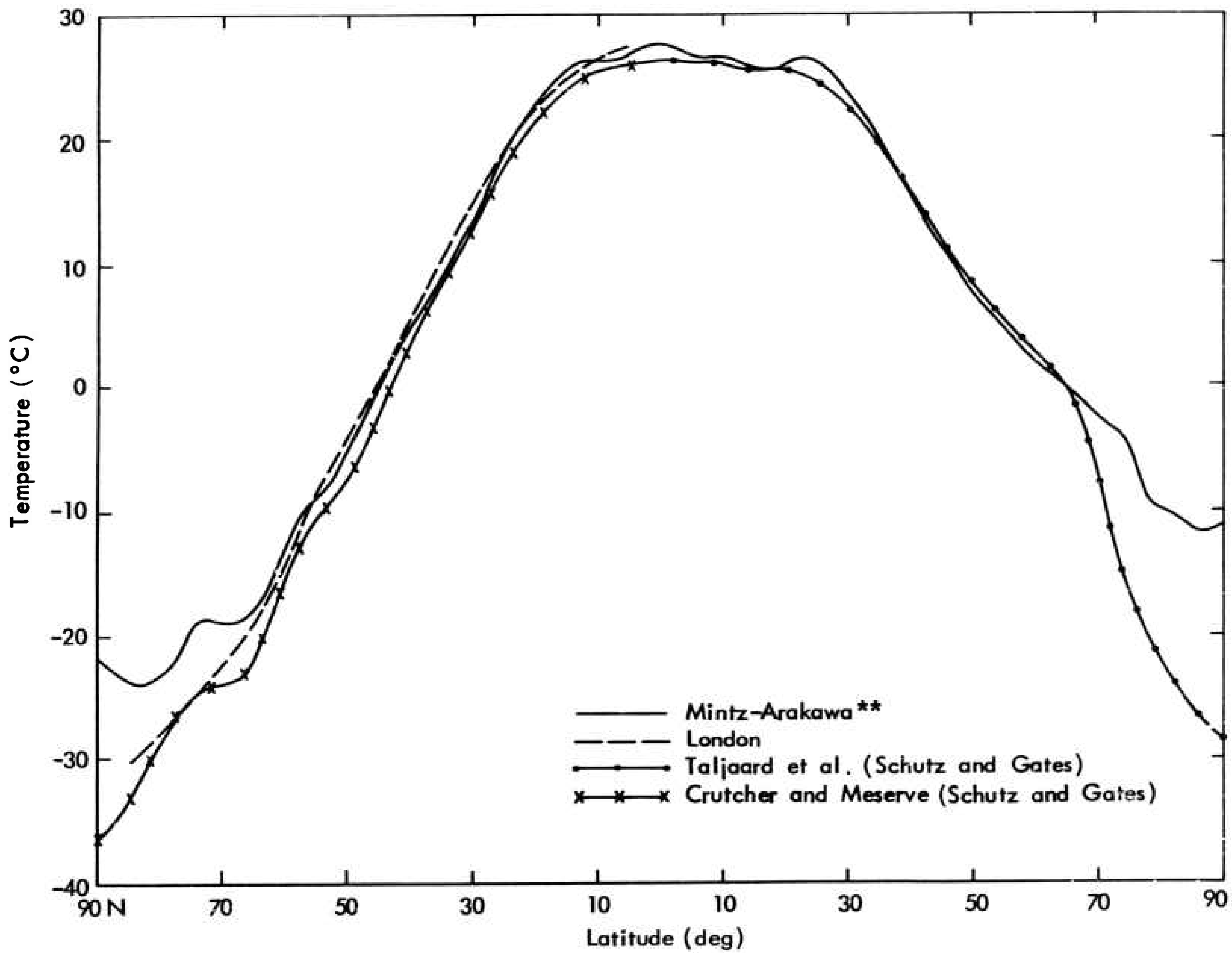

Fig. 3-The zonally averaged ground and surface air temperature.

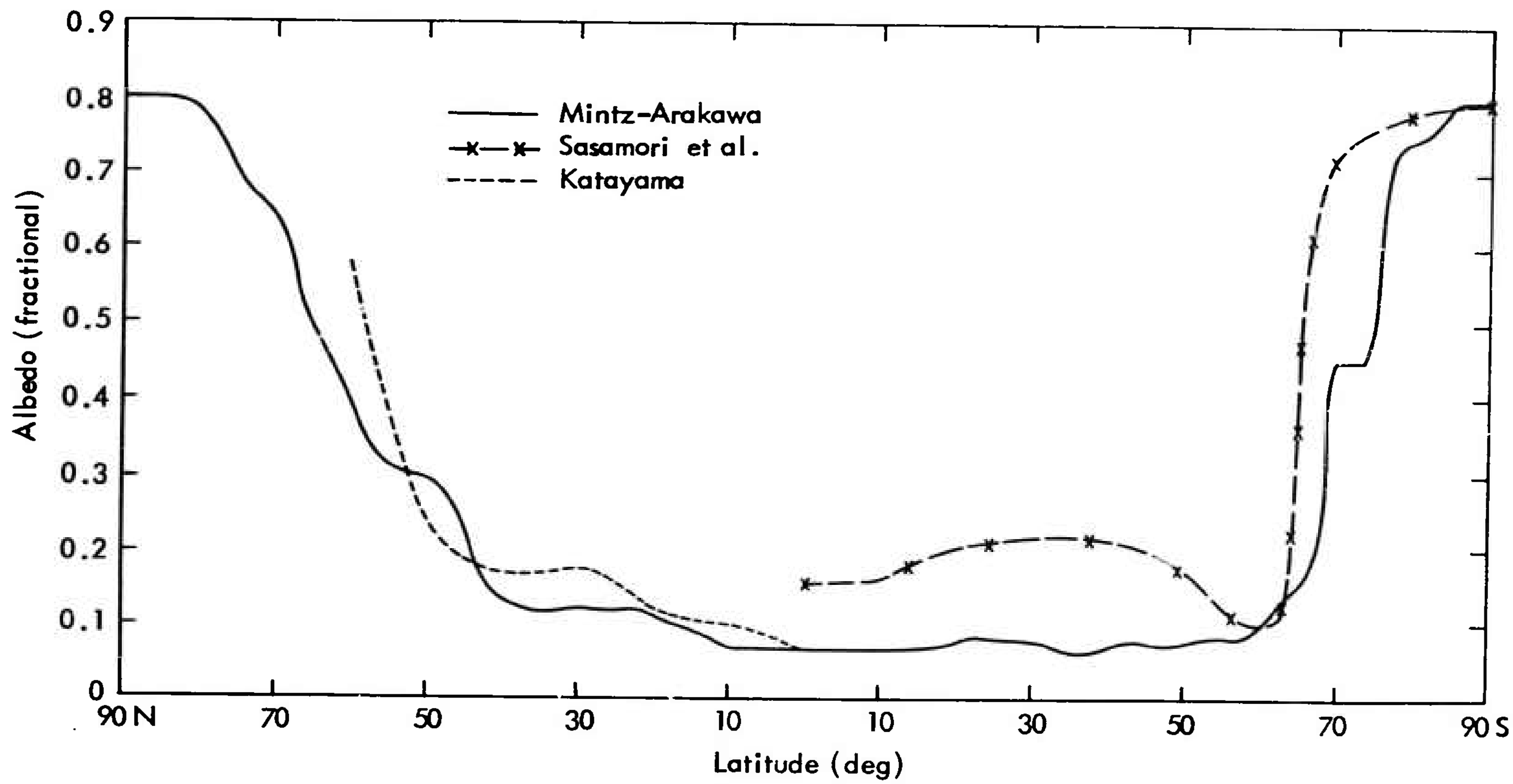

Fig. 4-The zonally averaged surface albedo.

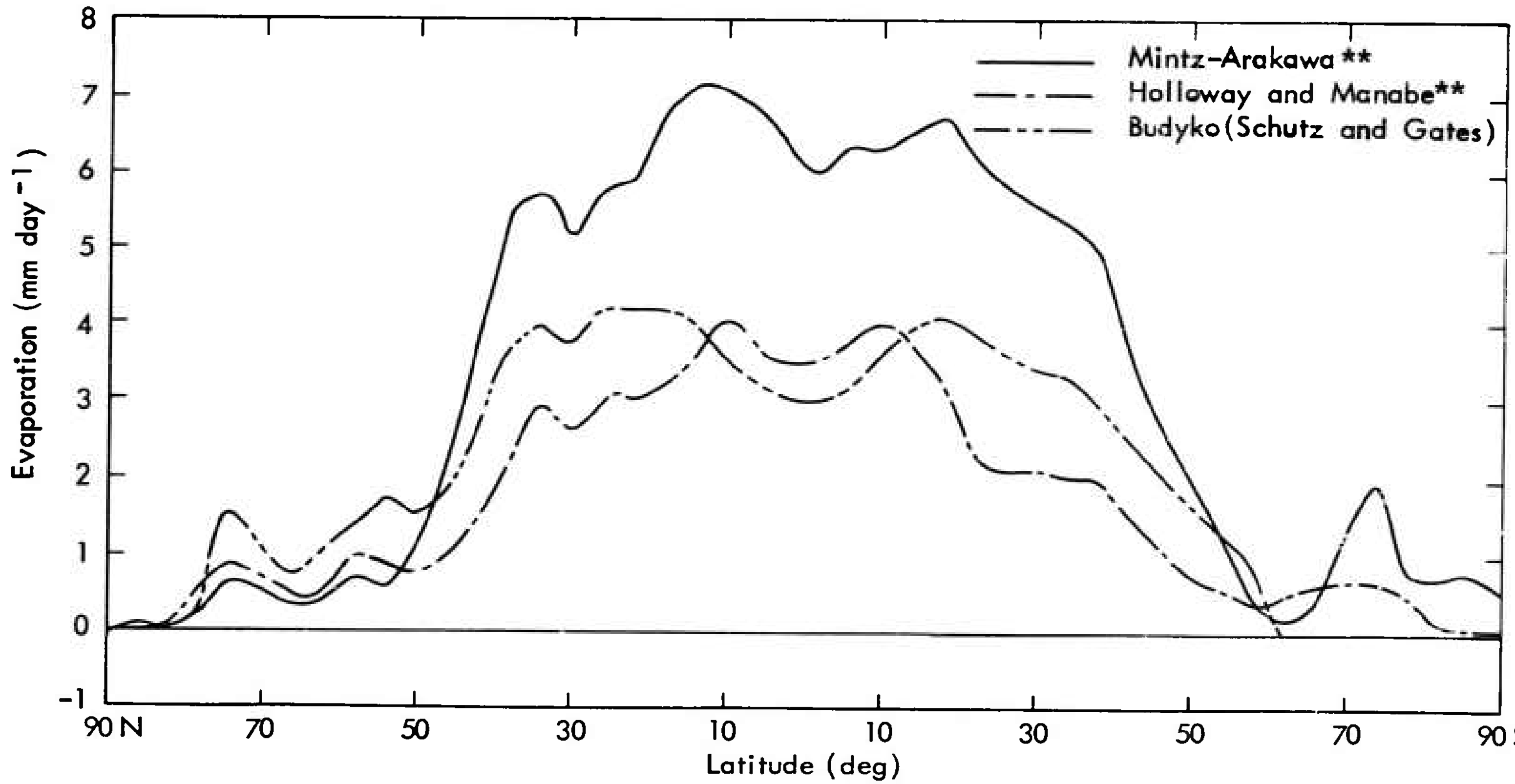

Fig. 5-The zonally averaged evaporation.

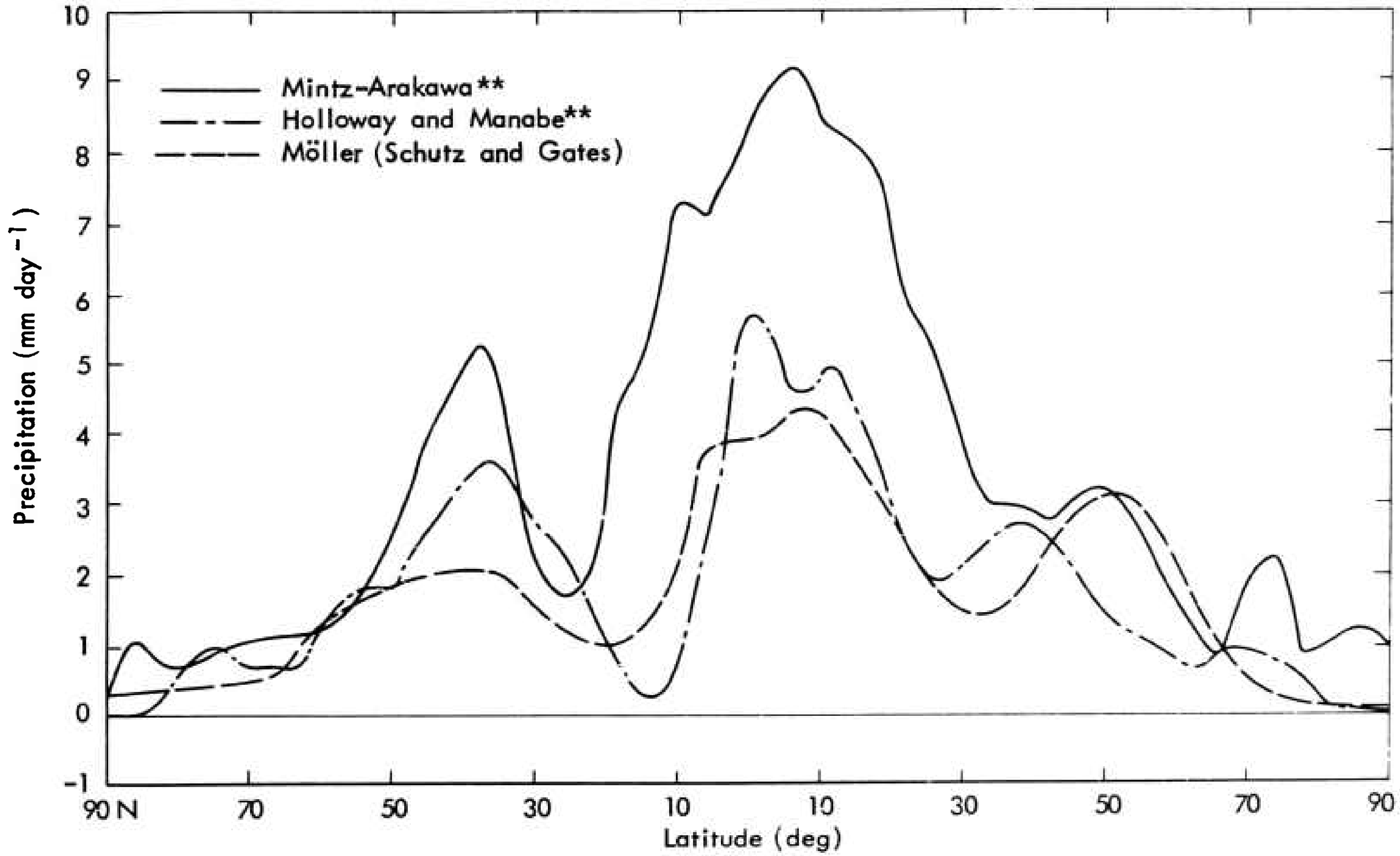

Fig. 6-The zonally averaged precipitation.

rates for the two general circulation models, as well as the climatological data of Möller (1951) as given by Schutz and Gates (1972). For both rates the Mintz-Arakawa model shows almost twice as much moisture conversion in the tropics as do the other distributions. It is evident that the hydrologic cycle in the Mintz-Arakawa model proceeds at much too rapid a pace.

In order to complete the consideration of the heat budget, we must include the sensible heat exchange. The flow of sensible heat may occur either to or from the surface of the earth. When we examine the zonally averaged distribution of sensible heat flux in Fig. 7, as calculated by the Mintz-Arakawa model, it appears that the flux is downward over as much of the earth as it is upward. Budyko (1963), as collected by Schutz and Gates (1971), and Holloway and Manabe (1971), however, show only an upward transfer of sensible heat in their zonal distributions.

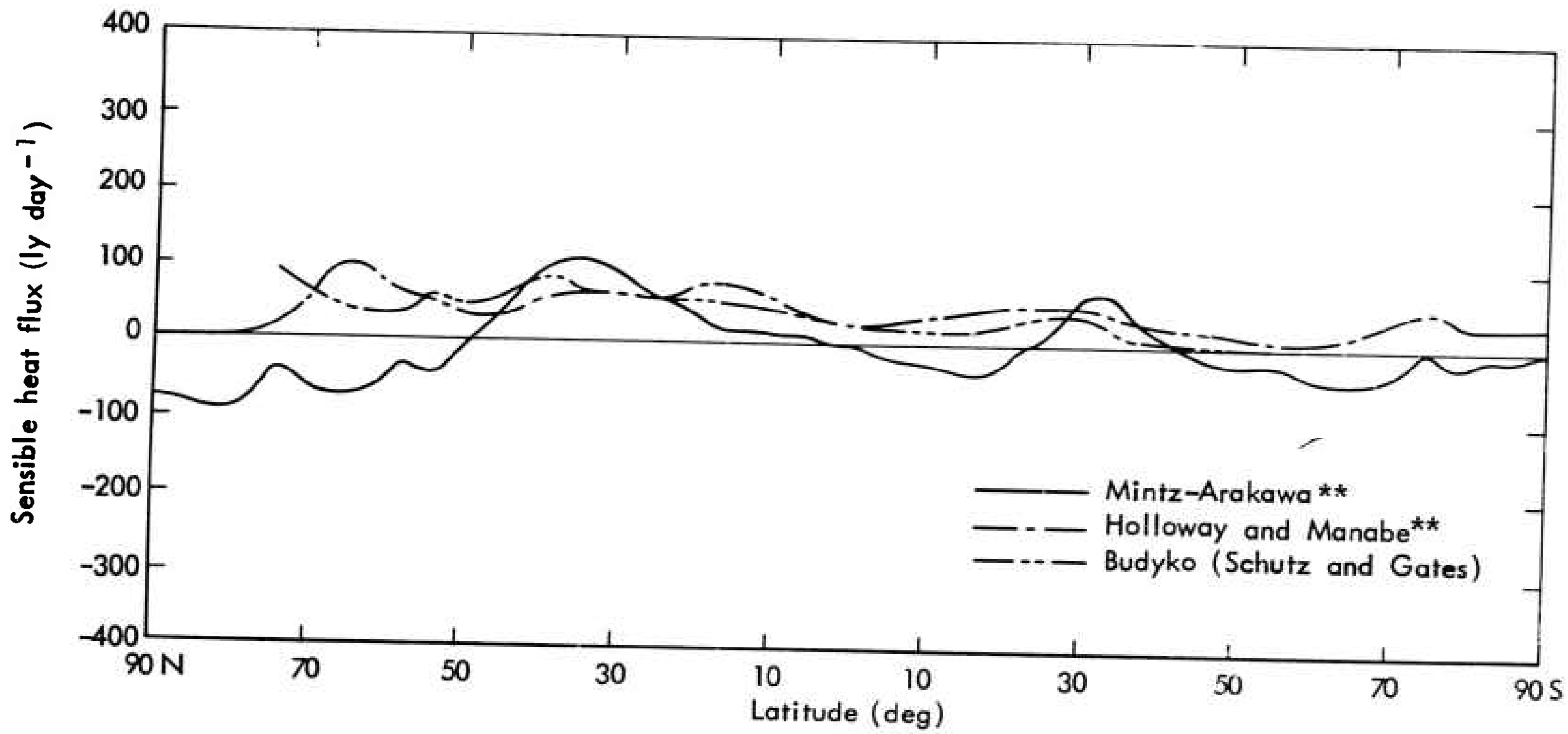

Fig. 7-The zonally averaged sensible heat flux.

III. SHORT-WAVE RADIATION

The incoming solar radiation used by the model for January is based on a solar constant of 2.0 ly min^{-1} (cal cm^{-2} min^{-1}), and calculated as a function of the time-dependent solar orbital parameters and local solar zenith angle. Since the total solar radiation reaching the top of the atmosphere is unaffected by the model, it should closely resemble other distributions of incident solar radiation, being dependent only on the value chosen for the solar constant and whether January or the three winter months (December, January, and February) are being characterized. The zonal averages of the January incident radiation specified by the Mintz-Arakawa model are shown in Fig. 8. Also shown for the northern hemisphere are values from Katayama (1966, 1967) for January, based on a solar constant of 1.94 ly min^{-1}, and from London (1957), based on a solar constant of 2.0 ly min^{-1} and averaged over the three winter months. For the southern hemisphere the values of Sasamori et al. (1972) for January 15, based on a solar constant of 2.0 ly min^{-1}, are given.

Of the incoming solar radiation, roughly 15 percent is absorbed by the atmosphere (which is thus directly heated), 35 percent is reflected back to space by the clouds, the atmosphere (back scattering), and the ground, and 50 percent is absorbed by the surface of the earth. The latter energy may be stored temporarily in the form of an increase in the surface temperature but is eventually lost by the earth's surface in the form of long-wave radiation, sensible heat, and latent heat, thus heating the atmosphere indirectly.

In the Mintz-Arakawa model, atmospheric absorption of solar radiation is calculated for each layer successively as a function of the water-vapor content of that layer. Clouds are incorporated simply by assigning them as equivalent water-vapor content. All other gaseous and aerosol absorption is neglected. On the other hand London (1957) reports on the atmospheric absorption by ozone and clouds individually and water vapor and dust together. Katayama (1967) gives the absorption due to water vapor, dust, and clouds separately, and Sasamori

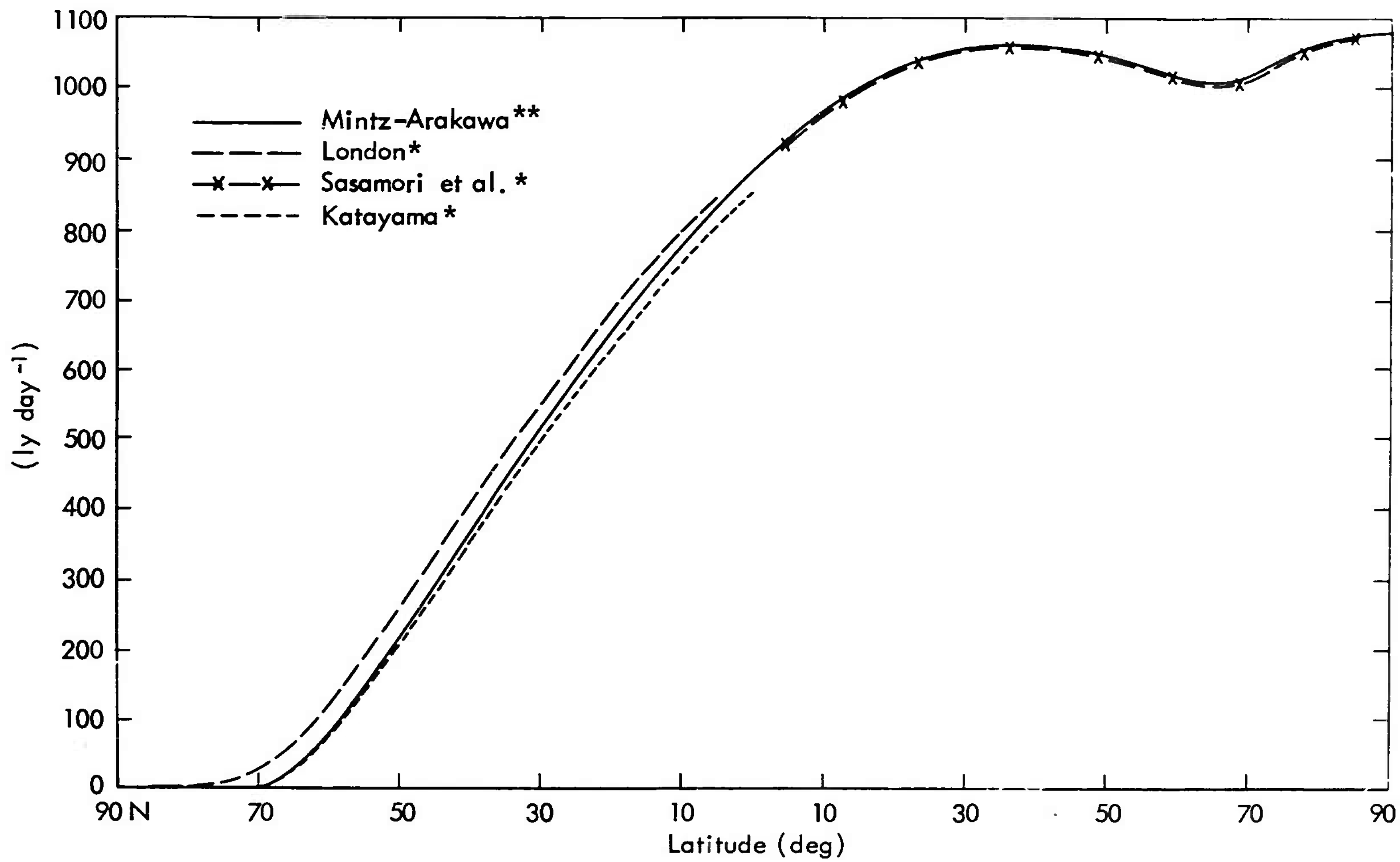

Fig. 8-The zonally averaged solar radiation incident on the top of the atmosphere.

et al. (1972) treat ozone, water vapor, and clouds separately and molecular oxygen and carbon dioxide together. The results of London and Sasamori et al. are given for the entire atmosphere, and those of Katayama for the troposphere. Thus their results cannot be compared with the Mintz-Arakawa values calculated for the individual layers.

The zonally averaged values of atmospheric absorption for the various data sets are given in Fig. 9. It should be noted that because the absorption of solar radiation is one of the smallest components of the radiation budget, the scale of this figure is five times larger than that used in the rest of the figures in this report. The data from Katayama are for the troposphere only. The upper curves for Mintz-Arakawa, London, and Sasamori et al. represent the total absorption in the atmosphere. The lower curve for Mintz-Arakawa is for the troposphere only, the difference between the two curves being due to the small amount of absorption by water vapor in the stratosphere. The lower curves for the data of London and Sasamori et al. do not include ozone absorption. Thus, if we assume that all ozone absorption occurs in the stratosphere and all other absorption in the troposphere, the lower curves represent the troposheric absorption curves for London and Sasamori et al., to be compared with the data of Katayama and the lower Mintz-Arakawa curve.

If we first look at this "tropospheric" absorption, it is apparent that the Mintz-Arakawa model absorbs considerably less solar radiation in the lower and middle latitudes than is indicated by the other investigators. This is particularly true when the results are compared with those of Sasamori et al. for the southern hemisphere and is at least in part due to the low amount of water vapor in the Mintz-Arakawa model. However, referring to Fig. 2, it appears that the Mintz-Arakawa water-vapor amounts are low between 20°N and 30°S, while the tropospheric absorption is low between 30°N and 60°S. This suggests that more fundamental deficiencies in the model may exist. One may be the lack of absorbers other than water vapor. Another may be the assumption that only that part of the solar radiation of wavelength greater than 0.9 μ is subject to absorption. Others (see, for instance, Dopplick, 1970) have divided the spectrum at 0.7 μ.

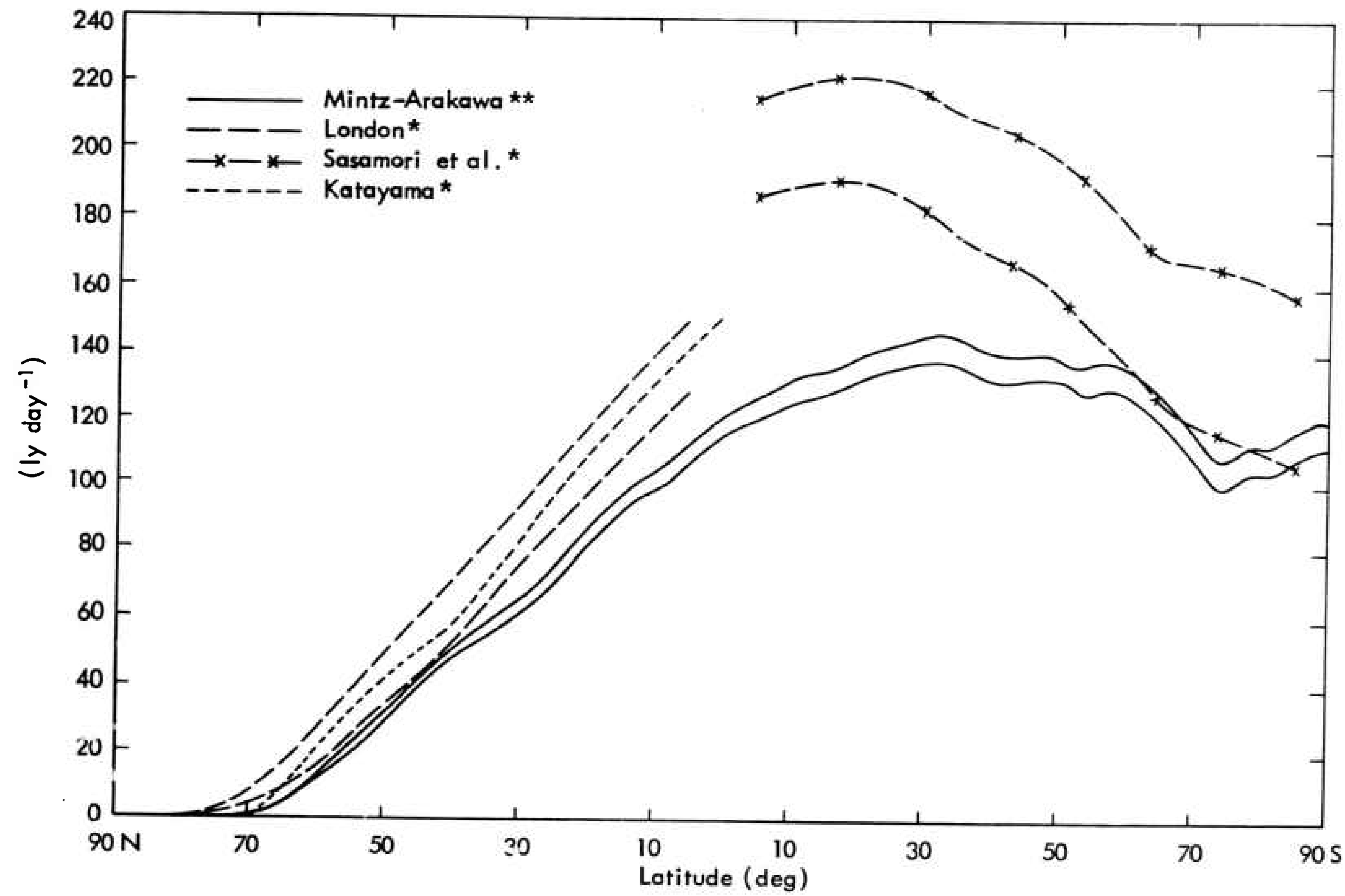

Fig. 9-The zonally averaged solar radiation absorbed by the total atmosphere (upper curves) and the troposphere (lower curves).

The tropospheric absorption is the quantity of interest when considering the solar heat input directly to the atmosphere. On the other hand, when considering the radiation arriving at the ground, we must look at the total depletion by absorption, including the stratospheric contribution. Looking at the upper curves of Fig. 9, we can see that the absence of ozone absorption in the Mintz-Arakawa model allows too much radiation to enter the troposphere. This will be commented on later as we follow the solar radiation through the model.

The zonally averaged distributions of solar radiation reflected and scattered back to space from the earth-atmosphere system for January, as calculated from the Mintz-Arakawa model, and as given by London (1957) for the northern hemisphere and by Sasamori et al. (1972) for the southern hemisphere, are shown in Fig. 10. In the low and middle latitudes most of the solar radiation lost to space is reflected from cloud surfaces. The contributions reflected from the earth's surface and scattered by the atmosphere are only of secondary importance. At higher latitudes (in January only the high latitudes of the southern hemisphere receive a significant amount of sunlight) reflection from the snow and ice-covered surfaces is of major importance also. The agreement between the distributions is reasonably good despite the fact that the cloudiness in the Mintz-Arakawa model (see Fig. 1) differs substantially from London's cloud data and that considered by Sasamori et al., who used the cloudiness data of van Loon (1972). Undoubtedly the insufficient absorption of solar radiation in the Mintz-Arakawa model means that the amount of solar radiation incident on the cloud tops is increased in comparison with the amounts present in the other studies. The solar radiation in the Mintz-Arakawa model has traversed one-quarter of the mass of the troposphere before reaching the highest 9 percent of the clouds, one-half the mass before reaching the next 44 percent of the clouds, and three-quarters of the mass by the time it reaches the final 47 percent of the clouds. Thus, not only the lack of ozone absorption in the stratosphere but also the reduced tropospheric absorption will contribute to the enhanced solar radiation reaching the cloud tops. This tends to compensate for the reduced cloud cover, so that the reflected radiation is not too different from that found by others. In

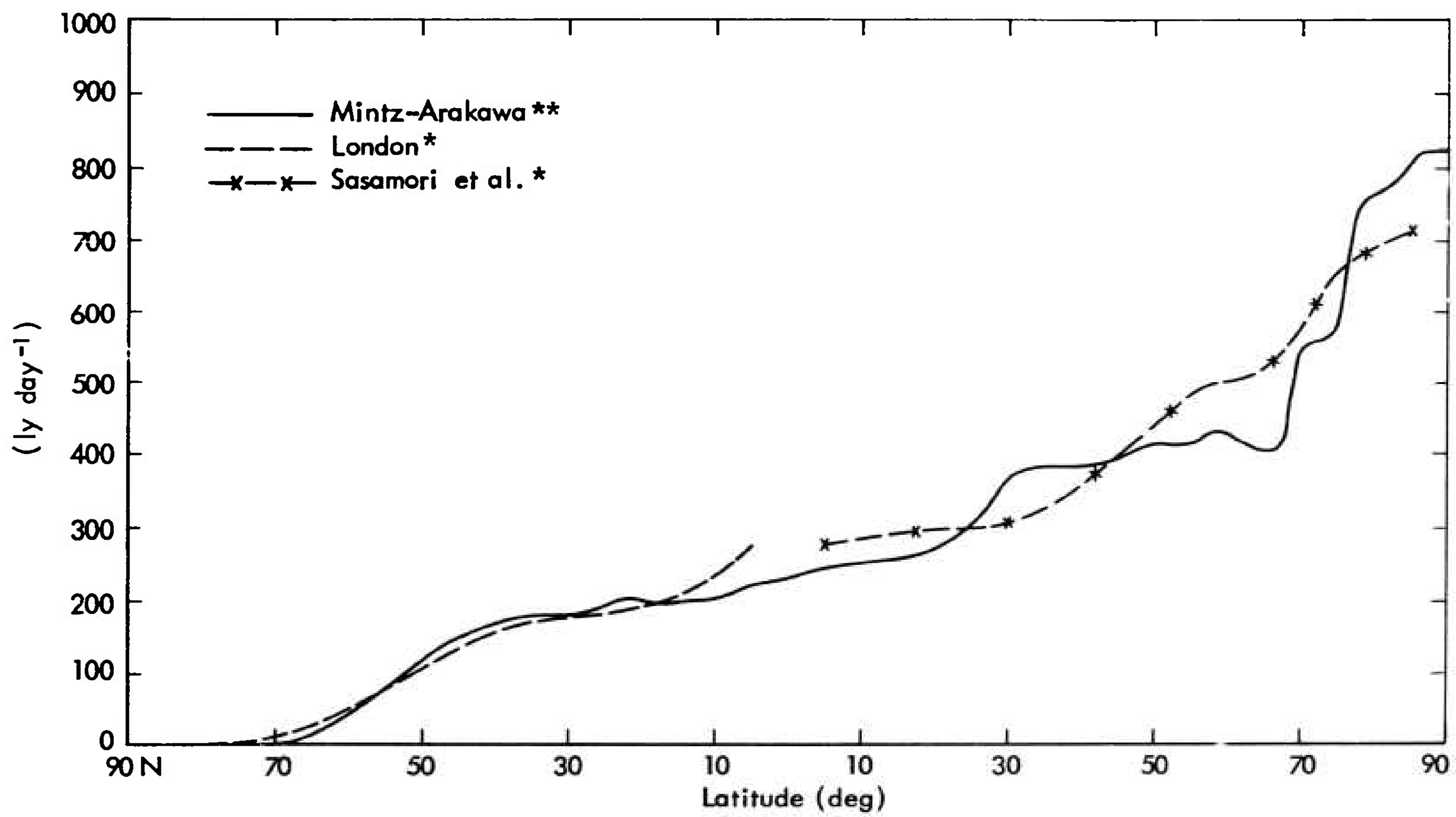

Fig. 10-The zonally averaged solar radiation reflected and scattered back to space from the earth-atmosphere system.

the southern hemisphere in particular, starting with this premise that more radiation is reaching the cloud tops in the Mintz-Arakawa model than in the other studies, the distributions of reflected solar radiation correlate well with the corresponding cloud distributions. Around 35°S and near the south pole the Mintz-Arakawa model has about the same or slightly more cloud cover than van Loon, and the reflected flux is greater than that of Sasamori et al. In the tropics the Mintz-Arakawa model has considerably less cloud cover but only slightly smaller amounts of reflected radiation. Only between 45°S and 75°S, where the difference between the smaller Mintz-Arakawa cloud cover and that of Sasamori et al. is greatest and the absorption discrepancy is somewhat reduced, is there a significantly smaller reflected flux in the Mintz-Arakawa model.

The zonally averaged distributions of solar radiation incident upon the earth's surface in January are shown in Fig. 11. In addition to the values produced by the Mintz-Arakawa model, the results of London, Sasamori et al., Katayama, and Budyko (1963) as given by Schutz and Gates (1971) are also presented. As would be expected, given the lower amounts of absorption found for the Mintz-Arakawa model, the model's solar radiation incident upon the surface is larger than any of the values reported by the other studies. In middle and high latitudes of the winter hemisphere the various distributions are quite similar, not so much because greater accuracy has been achieved there but rather simply because the hemisphere is relatively dark. The details of the curves in Fig. 11 can be explained quite well on the basis of our previous observations about the solar radiation in the Mintz-Arakawa model. In the tropics there is insufficient absorption in the model, and therefore too much radiation reaching the ground. From 30°S to 35°S the solar radiation reaching the ground is about the same in the model as in the other data sets. In this region the model reflects more than the others due to a fairly high cloud cover, and this high reflection compensates for the insufficient absorption. Proceeding towards higher southern latitudes, the absorbed amounts remain smaller in the model while the relative amount of reflected radiation decreases, so the curves in Fig. 11 diverge with more radiation reaching the ground in

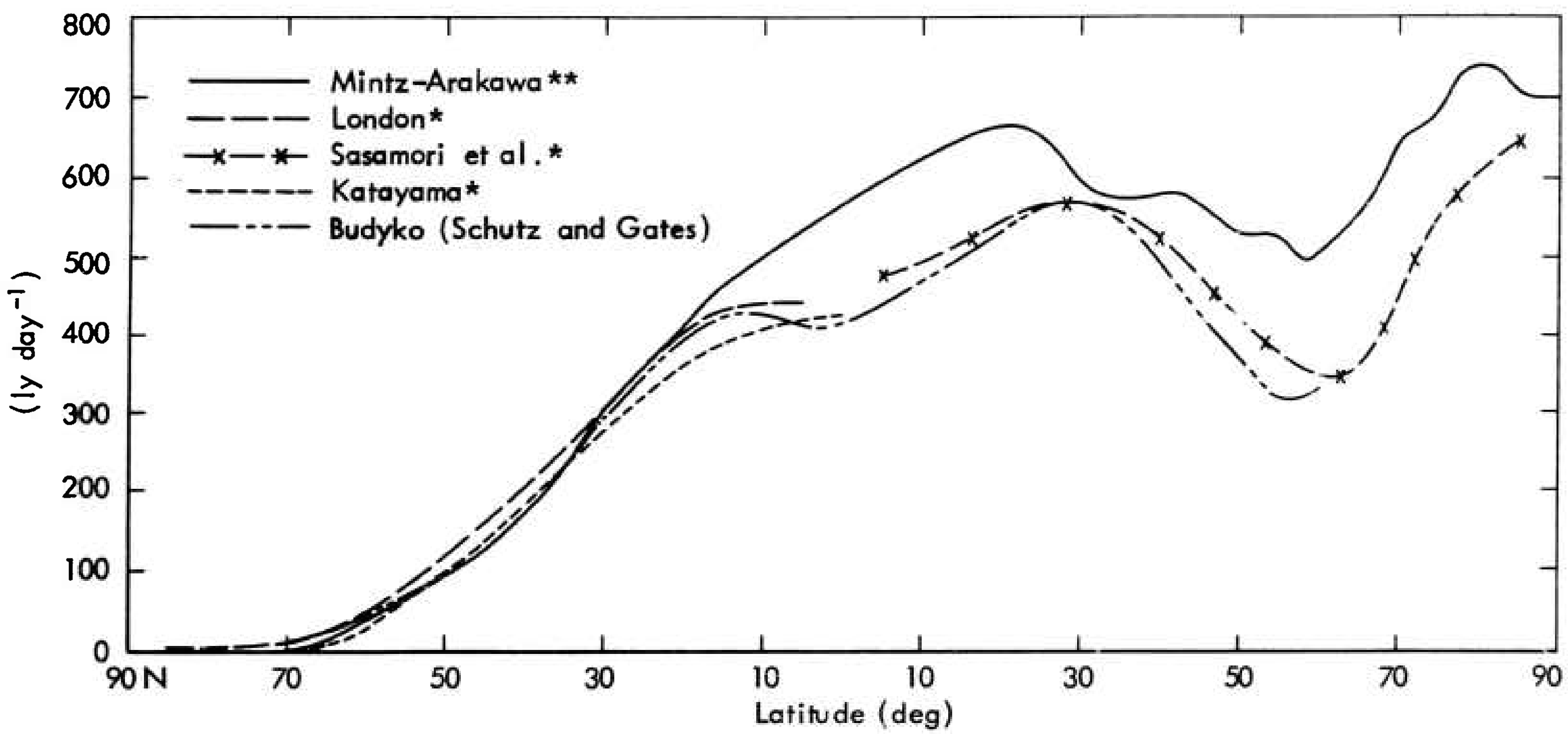

Fig. 11-The zonally averaged solar radiation incident on the earth's surface.

the model. The largest discrepancies are reached around 60°S to 70°S, where the Mintz-Arakawa cloudiness reaches a relative minimum and both absorption and reflection are low.

Figure 12 presents the zonally averaged January values of that part of the incident solar radiation absorbed by the earth's surface. The same studies are reported on as in the previous figure except that Budyko values are replaced by those of the Geophysical Fluid Dynamics Laboratory (GFDL) model (Holloway and Manabe, 1971). A comparison of Figs. 11 and 12 clearly illustrates the strong effect the large snow-surface albedo values have in the high latitudes of the southern hemisphere.

The planetary albedo is defined as the ratio of the solar radiation reflected and scattered to space to the solar radiation incident on the earth-atmosphere system. Zonally averaged values for January as calculated by Katayama (1967), Sasamori et al. (1972), and the Mintz-Arakawa model are given in Fig. 13. In addition, recent satellite measurements by Vonder Haar (1972) and Raschke et al. (1973) are included. As pointed out by Vonder Haar and Suomi (1971), the satellite observations tend to yield lower albedos than the other studies do. The planetary albedo of the Mintz-Arakawa model appears to lie within the range of the other values.

In summary, then, comparing the Mintz-Arakawa model with other data, we find insufficient absorption and, in a limited region, insufficient reflection of the solar radiation as it passes through the atmosphere. This allows too much solar radiation to reach and be absorbed at the earth's surface. When modifying the model, care should be taken to correct the cloud, water-vapor, and ozone amounts, and possibly also the albedo values simultaneously.

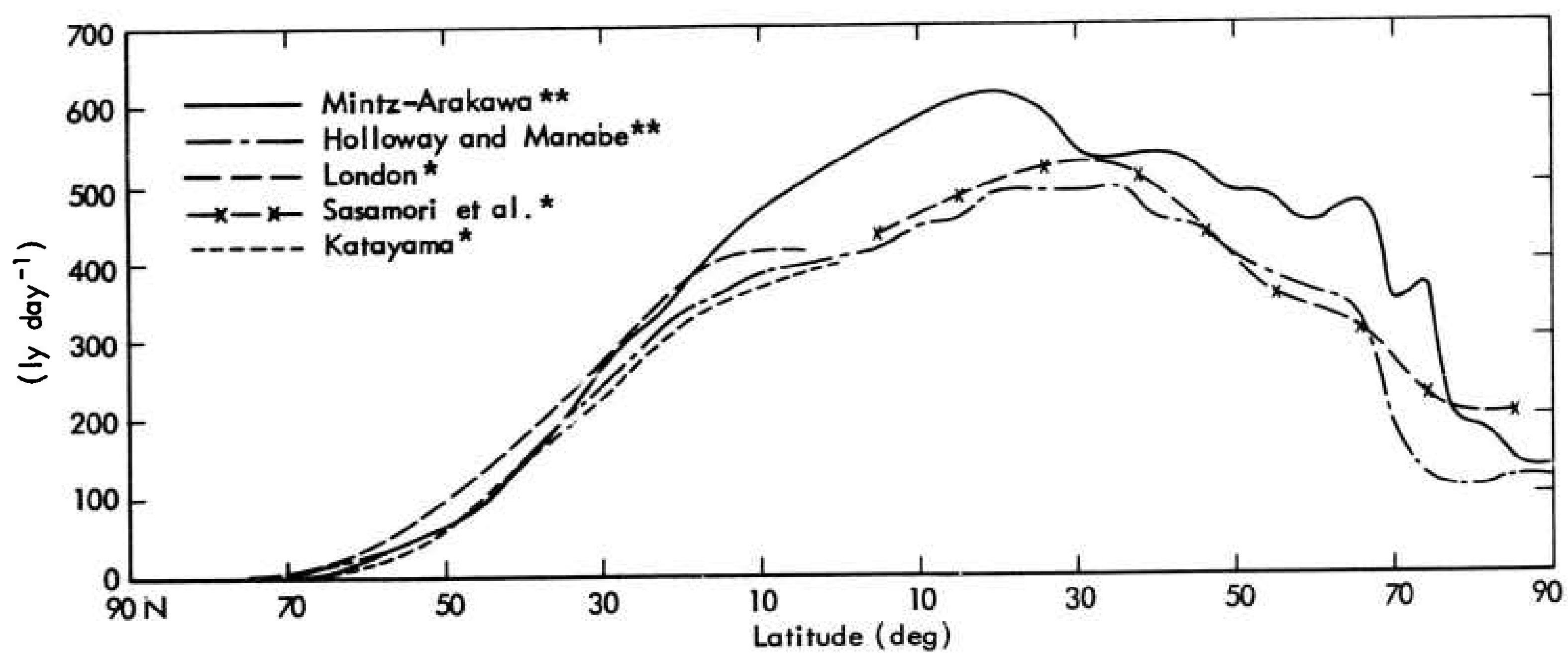

Fig. 12-The zonally averaged solar radiation absorbed by the earth's surface.

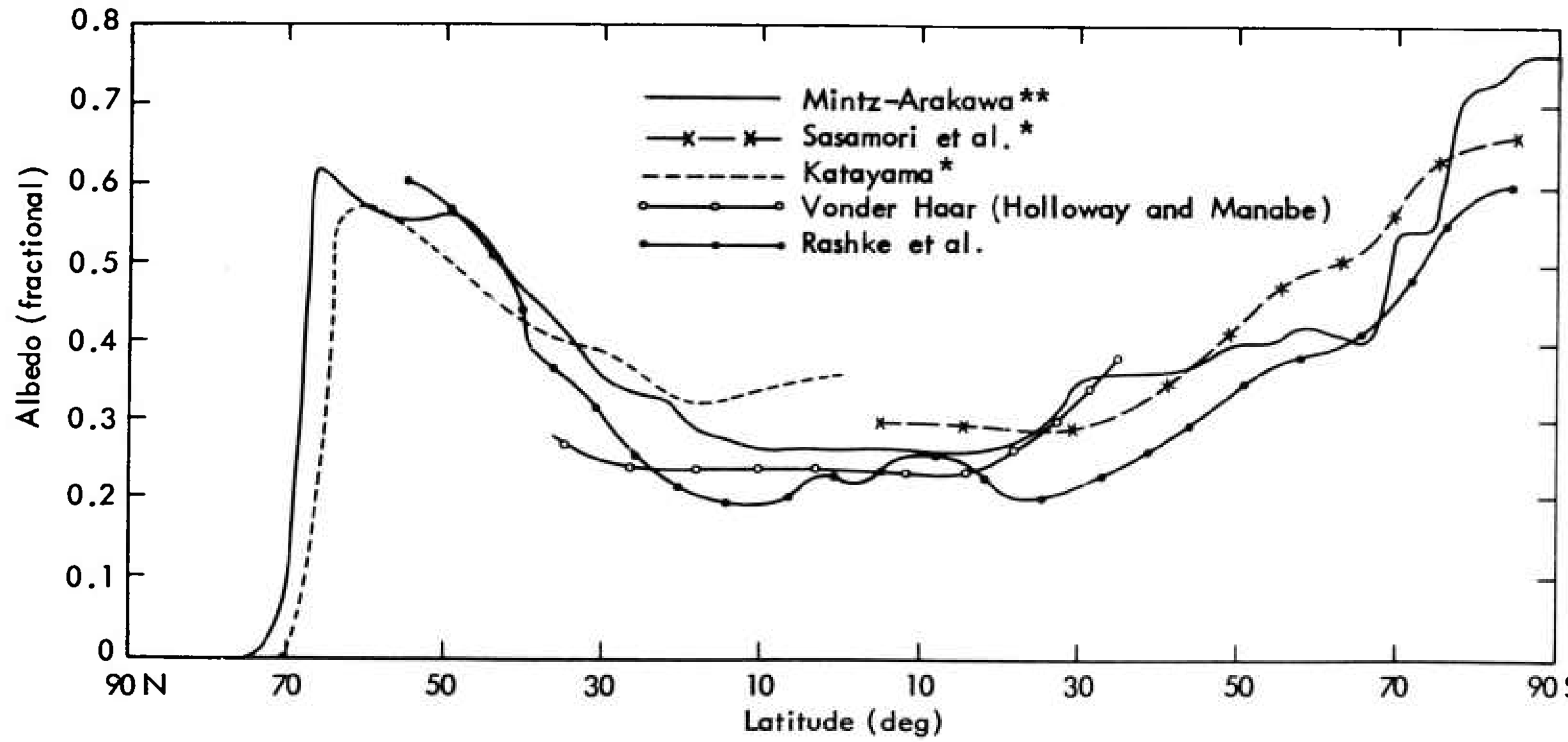

Fig. 13-The zonally averaged planetary albedo.

IV. LONG-WAVE RADIATION

Values of the net outgoing long-wave radiation flux at the 200-mb level were generated for the Mintz-Arakawa model. The January zonal profile is given in Fig. 14. Also presented are the net fluxes of Katayama (1967) and Haurwitz (1972), taken at around 200 mb, and those of London (1957), Holloway and Manabe (1971), Vonder Haar (1969) as reported by Holloway and Manabe, Sasamori et al. (1972), and Raschke et al. (1973), all taken at the "top" of the atmosphere. The distributions of Vonder Haar and Raschke et al. were derived from satellite observations.

We would anticipate that the net fluxes taken at the 200-mb level should be smaller than the upward fluxes at the top of the atmosphere. This is the case except in the tropics and subtropics and especially between 15°N and 30°S, where the Mintz-Arakawa values are actually largest. However, these values appear to be unrealistically large, probably because the model fails to produce a realistic water-vapor content, thereby underestimating both the water-vapor mass path and cloud cover.

All the profiles except that derived from the Mintz-Arakawa model show a relative minimum near the equator, with maxima between 15° and 30° in each hemisphere. These slight peaks are the result of reduced cloud cover at these latitudes. As already noted the cloud cover produced by the Mintz-Arakawa model is considerably smaller than all the other distributions presented in Fig. 1 except Miller's (1970) and possesses an essentially flat distribution between 18°N and 18°S, with increasing cloud cover thereafter in each hemisphere. All the flux profiles in Fig. 14 show a general decrease with increasing latitude, as would be expected given the general decrease in temperature with increasing latitude. The profile produced by the Mintz-Arakawa model indicates that above 65°N and between 55°S and 75°S the rate of decrease of the outgoing flux diminishes, while south of 75°S the flux resumes its relatively steep decrease. These changes appear to be correlated with the distribution of cloud cover. In the latitudes where the rate

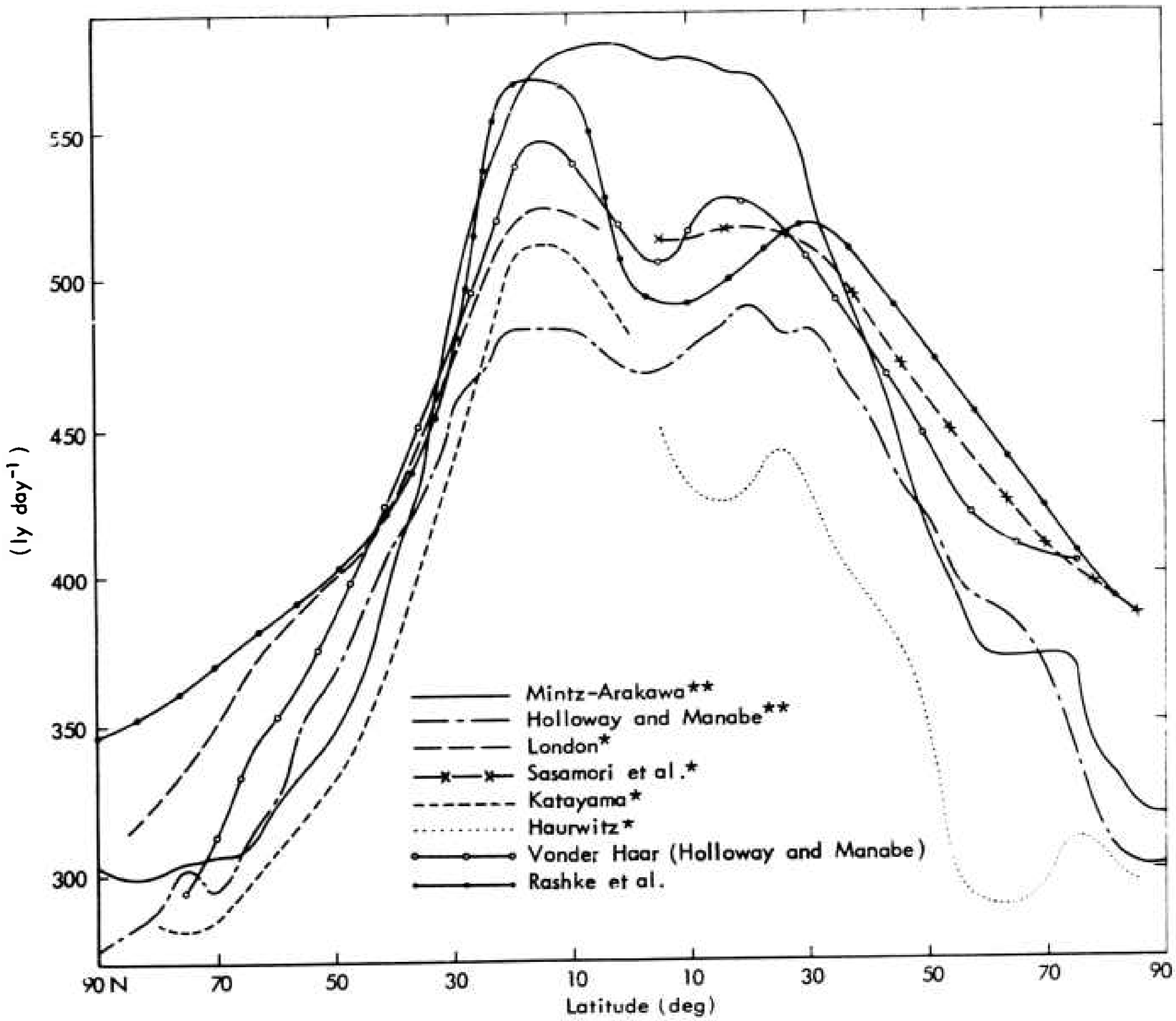

Fig. 14-The zonally averaged net long-wave radiative flux at the 200-mb level or the outgoing long-wave radiative flux at the top of the atmosphere.

of decrease of the flux is less, the cloud cover is relatively small, while in those latitudes where the flux decreases sharply, the cloud cover increases. The flux profiles of Vonder Haar (1969), Holloway and Manabe (1971), Haurwitz (1972), and Katayama (1967) all show some of these features.

It is interesting to examine Holloway and Manabe's (1971) results for the GFDL model, since theirs were the only ones, besides ours, which were developed in the context of the climate simulation problem with the use of a general circulation model. From about 50°N to 50°S the Mintz-Arakawa net fluxes at 200 mb are greater than Holloway and Manabe's upward fluxes. Holloway and Manabe comment that their cloud cover, which was taken from London (1957), may be inaccurate in the low latitudes, and we have already noted that the Mintz-Arakawa cover is quite small. In the higher latitudes of both hemispheres the agreement is considerably better.

It is presently not possible to explain the discrepancies between the available theoretical values and the satellite values as represented here by Vonder Haar (Holloway and Manabe, 1971) and Raschke et al. (1973). It should be noted, however, that considerable disagreement has arisen as a result of different interpretations of the satellite data (e.g., Winston, 1972, Suomi and Vonder Haar, 1972). Examination of the two sets of satellite values given in Fig. 14 shows that the agreement is at best qualitative. Other satellite data (e.g., Winston, 1969) do not show any better agreement with either of these two satellite distributions.

The net infrared radiative flux at the earth's surface has been calculated for January and is presented in Fig. 15. Also included are the results of the various other investigatons just discussed, excluding the satellite studies. The general form of the distribution is again closely tied to the distribution of cloudiness. Thus at latitudes where the cloud cover is greater, there is a greater downward flux at the earth's surface and the net flux at the surface, which is upward, is reduced. This is particularly evident in the vicinity of the intertropical convergence zone and the polar fronts, where there are relative minima of the net surface flux.

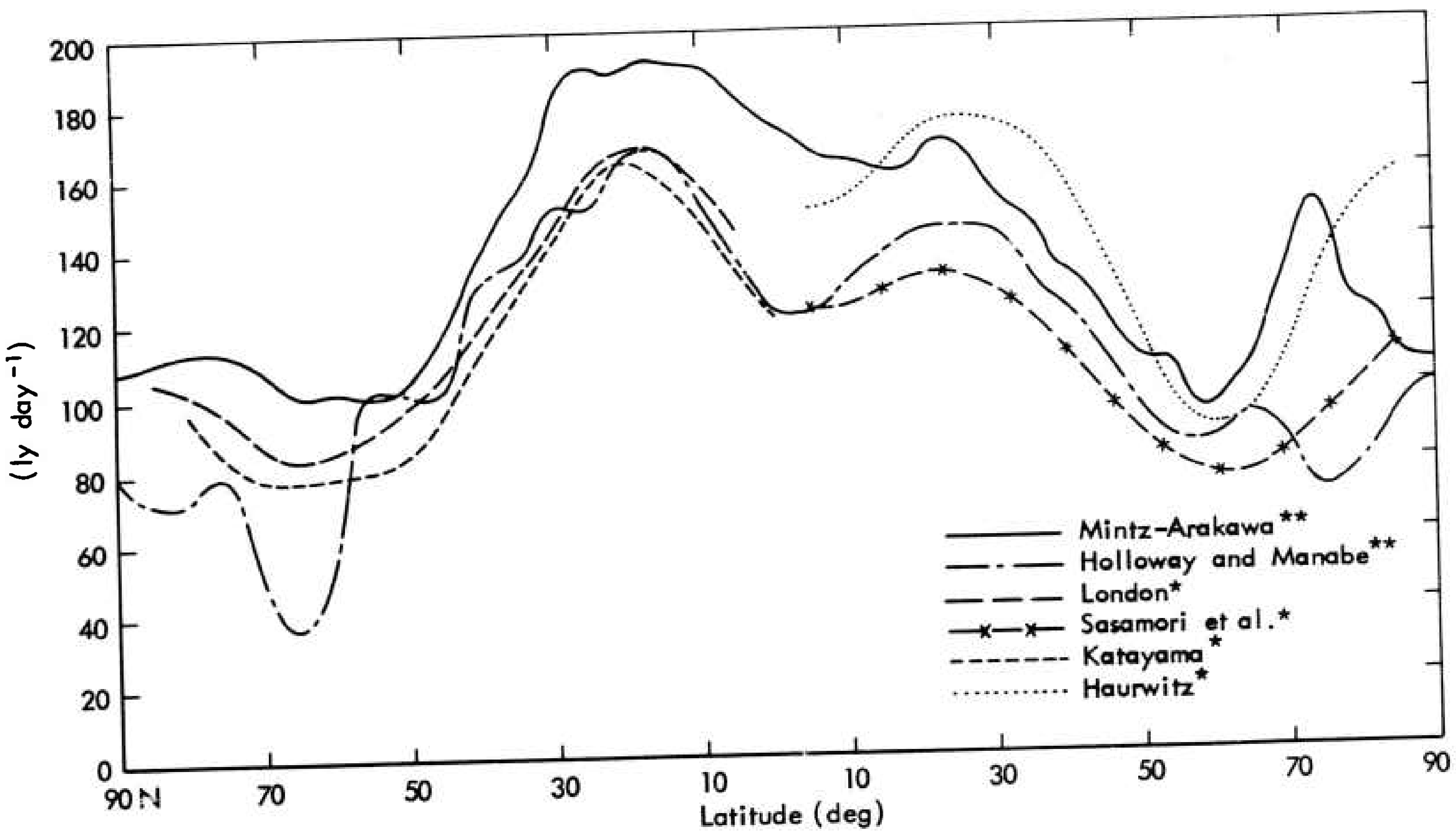

Fig. 15-The zonally averaged net long-wave radiative flux at the earth's surface.

Although the Mintz-Arakawa distribution of the net surface flux has a form somewhat like that of the other profiles presented in Fig. 15, it differs substantially from them in various ways. For the most part its values are largest, being anywhere from 10 to 30 ly day^{-1} larger than the other values. In the equatorial latitudes, where the differences are greatest, the amount of precipitable water generated by the Mintz-Arakawa model is considerably lower than the climatologically derived amounts used in all the other studies. The fact that the Mintz-Arakawa atmosphere has less moisture than the others means that the downward flux at the surface will be smaller and accordingly the net upward flux greater. At higher latitudes the agreement among the water-vapor concentrations is much better, as is the agreement between surface flux distributions.

The cloud cover generated by the Mintz-Arakawa model in the tropical latitudes is approximately 20 percent lower than the climatological values used by the other studies. Also it is approximately constant between 20°N and 20°S, while the climatological values show a slight peak around the equator. These differences will certainly contribute to the discrepancies between the Mintz-Arakawa net surface flux distribution and those calculated by others.

It is also possible that differences in the surface temperatures may account for some of the discrepancies between the net surface flux profile of Mintz-Arakawa and those of the other studies. The surface temperature profiles available are given in Fig. 3. Only in the polar latitudes do the differences appear to be significant. There the Mintz-Arakawa model produces temperatures as much as 30 degrees warmer than climatological values. The existance of these warmer polar surfaces will contribute to the larger net outgoing fluxes found by the Mintz-Arakawa model. In addition the model produces unrealistically large diurnal temperature variations, which are not apparent in the 30-day averages. Since the outgoing radiative flux has a T^4 dependence, larger values of average outgoing flux may be generated even though the average ground temperatures are the same.

In the southern hemisphere south of the polar front the Mintz-Arakawa model first shows an increase in the net flux and then a

decrease beyond 75°S. This pattern is clearly tied to the distribution of cloudiness in the high latitudes, where the cloud cover first decreases and then increases. The same feature exists in the northern hemisphere but is much less well developed because there is less cloud cover. None of the other studies show such extreme variations of the net long-wave radiation.

In the polar latitudes of the southern hemisphere the net surface fluxes, as calculated by Sasamori et al. (1972) and Haurwitz (1972), are only 20 ly day^{-1} lower than their peak hemispheric values. This quite substantial increase with increasing latitude is a function of the decrease in cloud cover and water-vapor content toward the pole. Holloway and Manabe (1971) show a smaller recovery, and the Mintz-Arakawa values, as already noted, have a local maximum not at the pole but at approximately 75°S.

Figure 16 presents the zonally averaged values of the net infrared flux divergence of the atmospheric column as calculated by the Mintz-Arakawa model and by the other investigations discussed in association with Fig. 15. These values are of interest because they provide a measure of the net infrared cooling in the column. It should be pointed out that the atmospheric column does not extend to the same level in all cases.

Generally the lower layers of the atmosphere contain enough water vapor and carbon dioxide to be relatively opaque in the infrared part of the spectrum. Thus since the spread between the effective emitting temperatures of the upward and downward fluxes passing through the bottom of the column is not large, the net flux at the surface will be relatively small. For this reason the meridional variations of the net flux divergence are primarily a function of the flux at the top of the column. We have already noted that the net flux at the top of the atmosphere decreases with increasing latitude because of the corresponding decrease in temperature. The same explanation accounts for the decrease of the net flux divergence with increasing latitude.

In the tropical latitudes the Mintz-Arakawa results are largest, in part at least because of the small cloud cover generated in those latitudes. One might have anticipated that Holloway and Manabe's (1971)

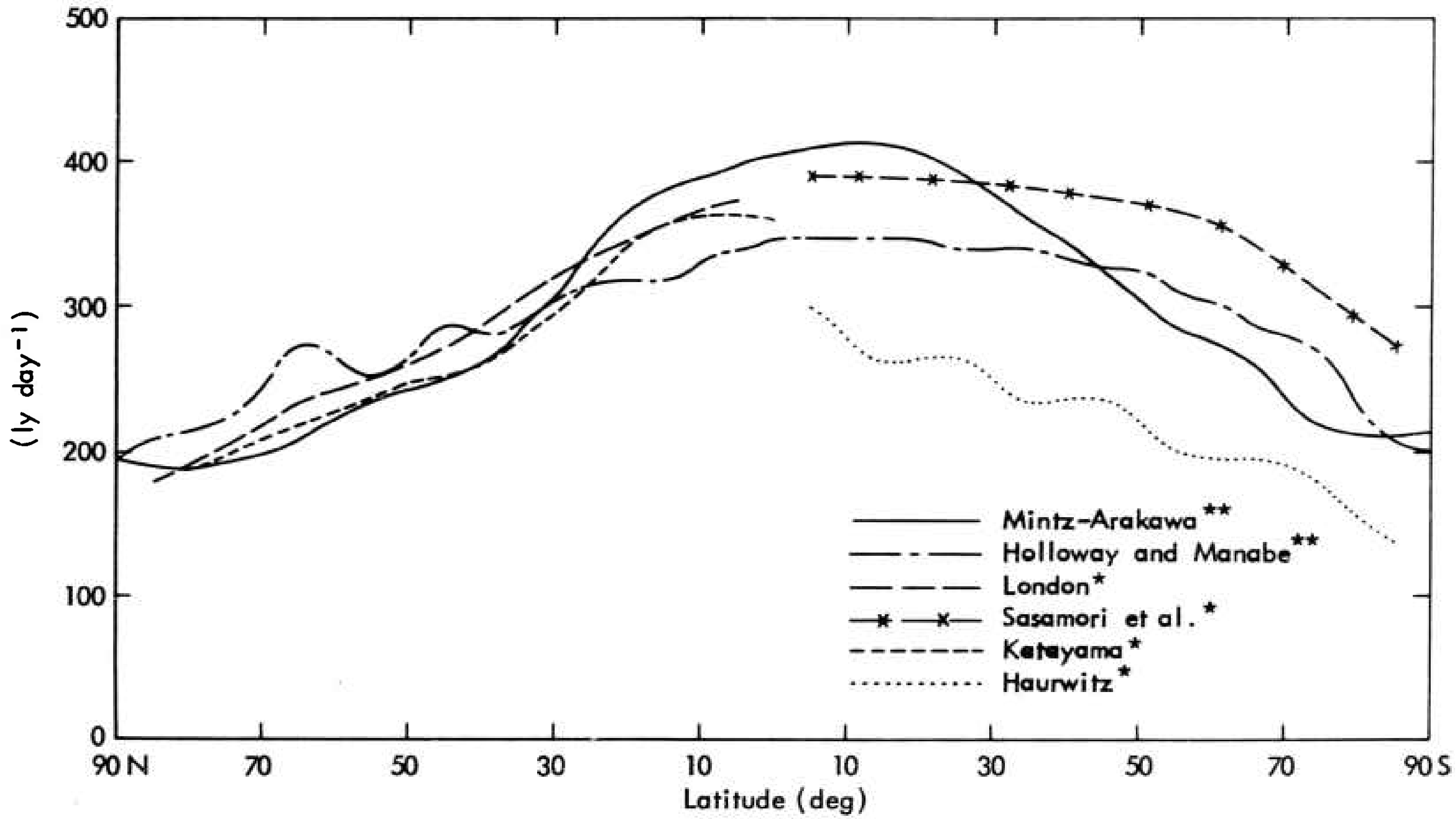

Fig. 16-The zonally averaged long-wave radiative flux divergence for various atmospheric columns.

values should have exceeded those of our model, since their column extends to the top of the atmosphere. However since they used London's (1957) climatological values of cloud cover, which are nearly 20 percent larger than those of the Mintz-Arakawa model in the tropics, this is not the case. At higher latitudes, where the cloud cover is in somewhat better agreement, Holloway and Manabe's values are indeed greater than those of the Mintz-Arakawa model. Actually, in the middle and high latitudes of the northern hemisphere the agreement between London (1957), Katayama (1967), and Mintz-Arakawa is quite good.

In the southern hemisphere there is a greater disparity between the various distributions. The values of Sasamori et al. (1972) are probably higher than they should be as the result of their using a normalization procedure which implicitly assumes that there is no overlapping between clouds at different levels. Unfortunately the cloud values used by Haurwitz (1972), while permitting the clouds to overlap, are based on an as yet poorly developed climatological record, so it is difficult to estimate the validity of those results either. Finally, since Holloway and Manabe's (1971) cloud cover was taken from seasonally transposed values of London (1957), those results are equally ambiguous.

Both the GFDL and Mintz-Arakawa general circulation models produce distributions of net flux divergence centered not at the equator but at approximately 10°S as would be expected during the southern hemisphere summer. In addition the net flux divergences of Sasamori et al. (1972) for the southern hemisphere are fairly constant from about 25°S to the equator. If the cloud distributions used by these three studies are examined (Fig. 1), it can be seen that all have lower values between 10°S and 15°S than at the equator, which would yield the sort of distribution of net flux divergence we find. However, a similar dip appears at 10°N to 20°N in both of those cloud-cover distributions which extend into the northern hemisphere, and this suggests that there should be a relative minimum in the flux divergence at the equator, something we do not find in any of the distributions. Warmer temperatures are skewed slightly toward the southern hemisphere and undoubtedly contribute to this distribution of the net flux divergence in the tropics.

In conclusion it would appear that in the tropical latitudes of the Mintz-Arakawa model too much long-wave radiation is escaping through the tropopause. If the entire tropospheric column is considered, this excessive loss is in part compensated for by the overestimation of the net upward flux at the surface. However, the flux divergence over the entire column is still somewhat too large. At higher latitudes in the northern hemisphere the flux divergences look reasonable, although near the pole the surface temperatures are probably too warm. In the mid-latitudes of the southern hemisphere the values are acceptable, but at higher latitudes the model does not seem to function as well. It should be pointed out, however, that because of the strong dependence of the long-wave fluxes on the distributions of clouds, moisture, and temperature, to criticize the radiative sections of the model would be premature.

V. RADIATION AND HEAT BUDGET

In this section the net radiative fluxes through the upper (tropopause) and lower surfaces of the Mintz-Arakawa model, as well as the nonradiative heat-flux terms at the lower surface, will be examined. The heat budgets for the model atmospheric column and earth-atmosphere system will also be considered. From the calculated heat budget for the atmospheric column the amount of heat that has to be transported horizontally to balance that budget will be derived. In addition, despite the fact that the ocean temperature is fixed, values for the ocean transport of heat required by the Mintz-Arakawa model will be calculated under the assumption that the values given by Newell et al. (1969) for the heat storage in the ocean can be used. The balances and their various components will also be compared with similar quantities given by others.

The zonal distribution of the January flux through the top of the model atmosphere (200 mb), shown in Fig. 17, is comprised of the incoming solar radiation minus the total reflected solar radiation and the net outgoing long-wave radiation. Although this flux is taken at the tropopause, it will be quite similar to the flux at the top of the atmosphere. Even though it is not necessarily true for any given latitude, London (1957) shows that globally the radiative fluxes at the tropopause and the top of the atmosphere are equal, with the ozone absorption of solar radiation just balancing the stratospheric net loss of long-wave radiation to space. The net flux at the tropopause is climatologically important, since the geographical distribution of this energy imbalance is the ultimate driving force for the atmospheric and oceanic circulations.

In addition to the flux at the tropopause from the Mintz-Arakawa model, Fig. 17 gives the fluxes in the northern hemisphere at the top of the atmosphere from London (1957) and at 200 mb from Katayama (1967), and in the southern hemisphere at the top of the atmosphere from Sasamori et al. (1972), as well as the global satellite data of Vonder Haar and Suomi (1971). While following the general trend of the other

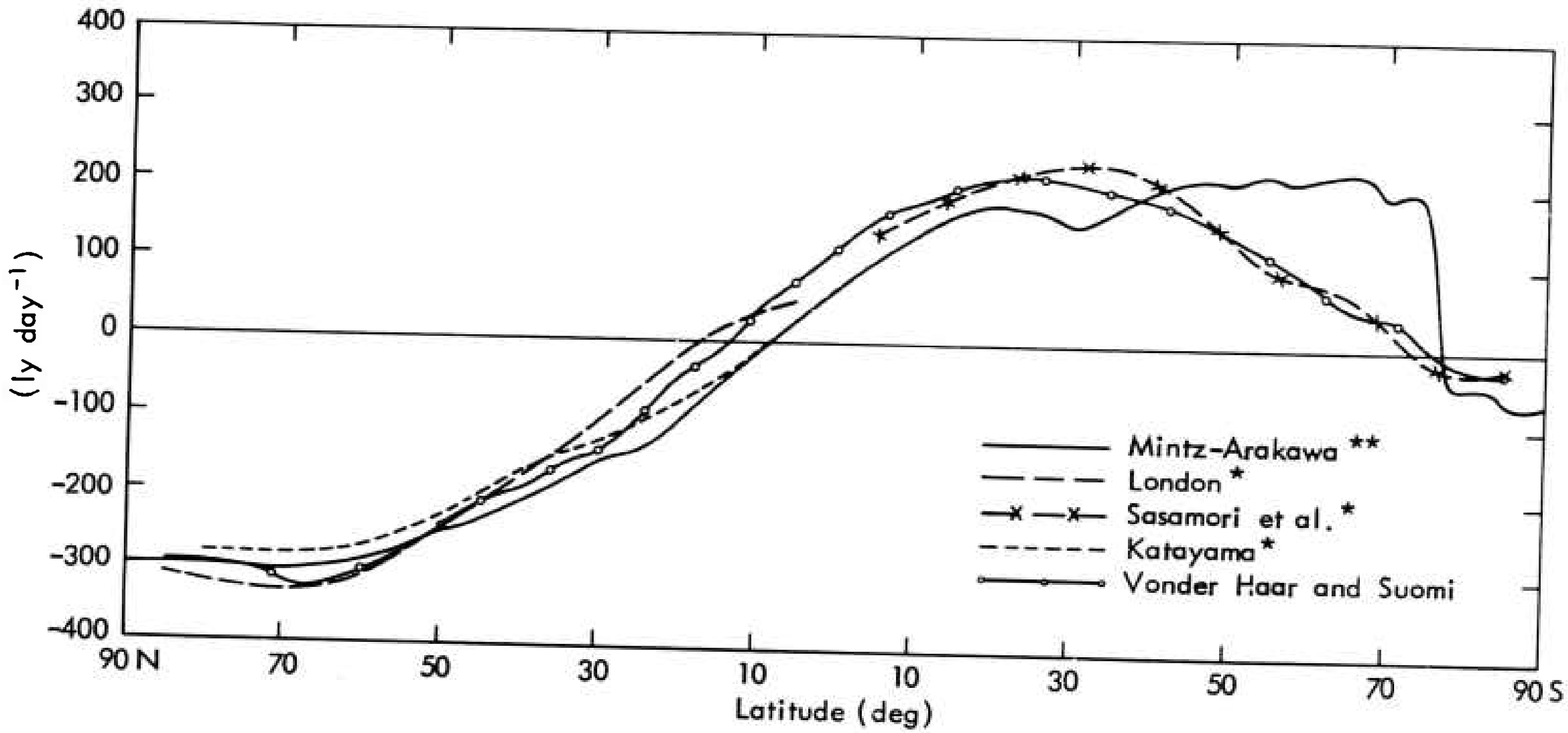

Fig. 17-The zonally averaged net radiative flux through the top of the atmosphere or 200-mb level.

distributions, the Mintz-Arakawa values are slightly smaller throughout most of the low latitudes and quite a bit larger between 50°S and 75°S. In the low latitudes, while both the model's net outgoing long-wave and incoming short-wave radiation are larger than the values reported by the studies with which they are compared, the differences are greater in the case of the long-wave radiation. Accordingly, the values of the model's net downward flux are somewhat smaller than those of the other studies presented in Fig. 17. The large peak in the high southern latitudes occurs in a region where the cloud cover and albedo of the model are relatively low compared with the other values available. Thus the amount of solar radiation reflected to space (see Fig. 10) is also relatively low. In addition, the net outgoing long-wave flux at 200 mb is comparatively small in that region. The cumulative effect is to produce an excessively large value for the net flux entering the troposphere in these latitudes. This will undoubtedly affect the atmospheric circulation in the high southern latitudes, a region where it is felt that the model's performance is less satisfactory (see, for instance, Gates, 1972).

We next look at the heat budget across the lower boundary of the model. Almost all the warming at the earth's surface is due to the absorption of incoming solar radiation. Cooling occurs due to both the net loss of long-wave radiation and the loss of heat through evaporation, the latter component being released into the atmosphere as latent heat of condensation when precipitation occurs. The earth's surface may also be cooled or heated due to the transfer of sensible heat, depending on whether the surface is warmer or cooler than the adjacent atmosphere.

The zonally averaged January heat budgets at the surface, and their components, are shown in Fig. 18 for the Mintz-Arakawa model, in Fig. 19 for the GFDL model discussed by Holloway and Manabe (1971), and in Fig. 20 for the data of Budyko (1963). Figures 18 and 19 include not only the long- and short-wave components but also the net radiation (the sum of the two parts), which is the only radiative quantity available from Budyko. On comparing the individual components of the heat budget in the three figures, it is evident that the Mintz-Arakawa model has the

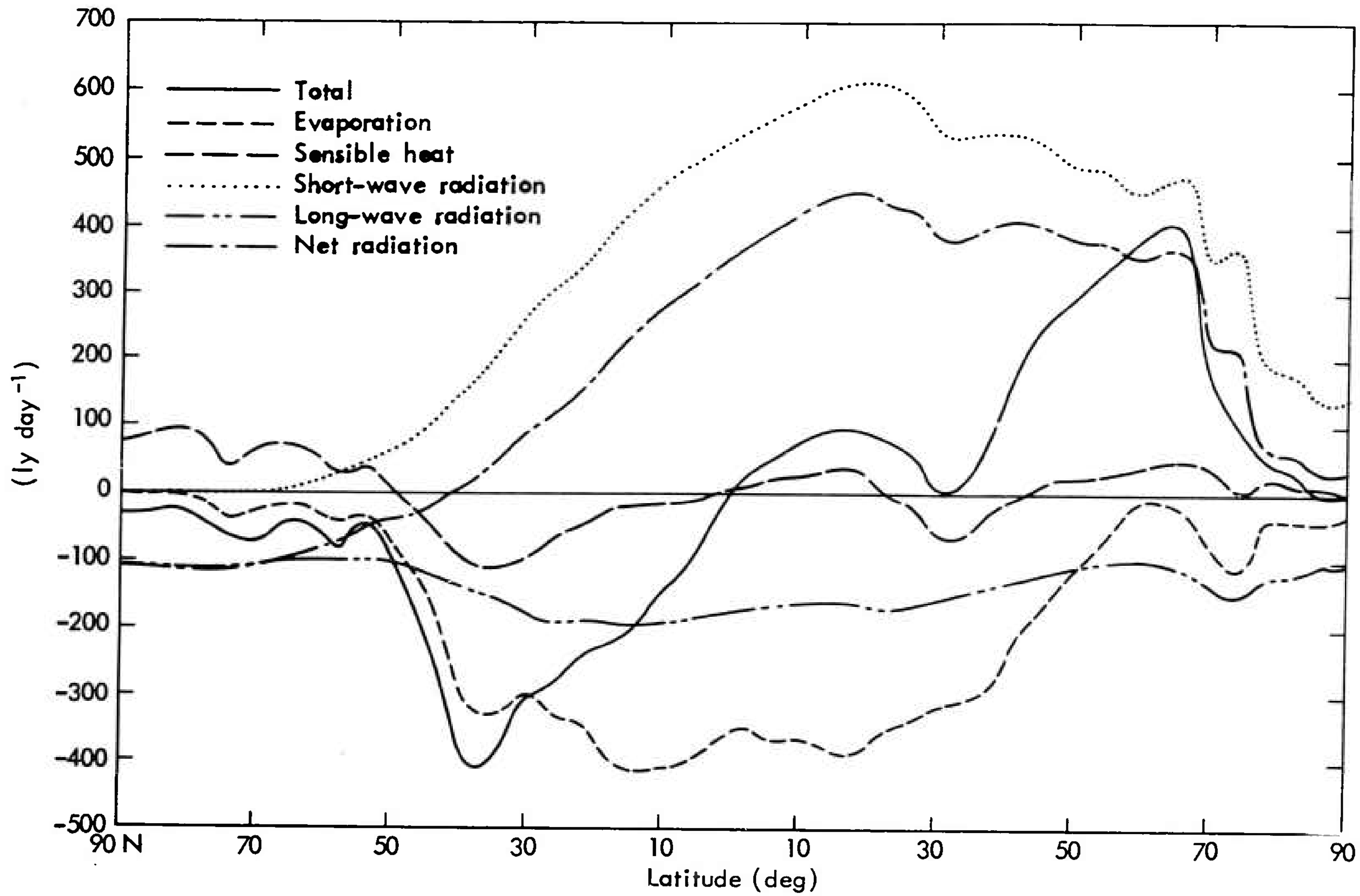

Fig. 18-The zonally averaged heat budget at the earth's surface for the Mintz-Arakawa model.

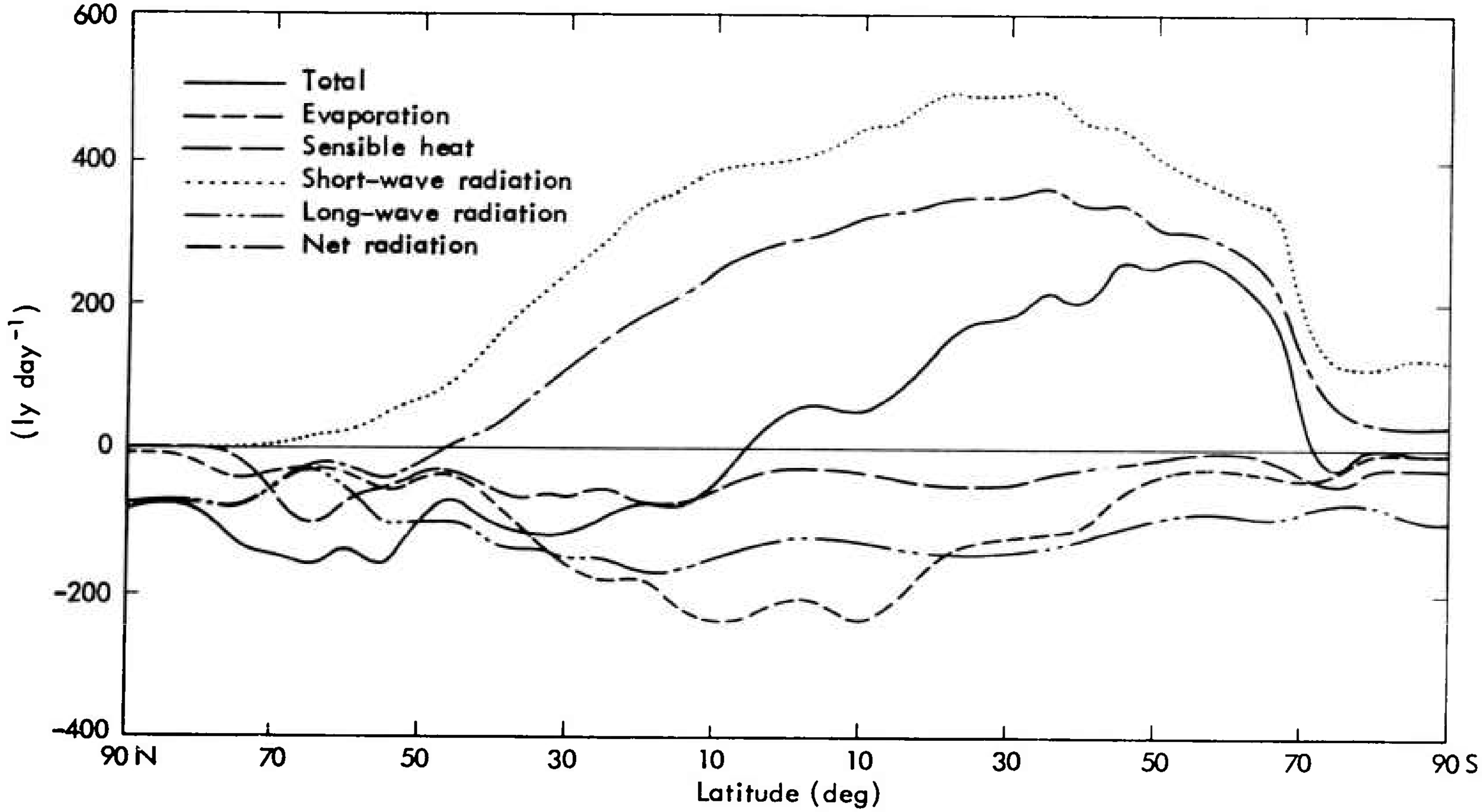

Fig. 19-The zonally averaged heat budget at the earth's surface for the GFDL model discussed by Holloway and Manabe (1971).

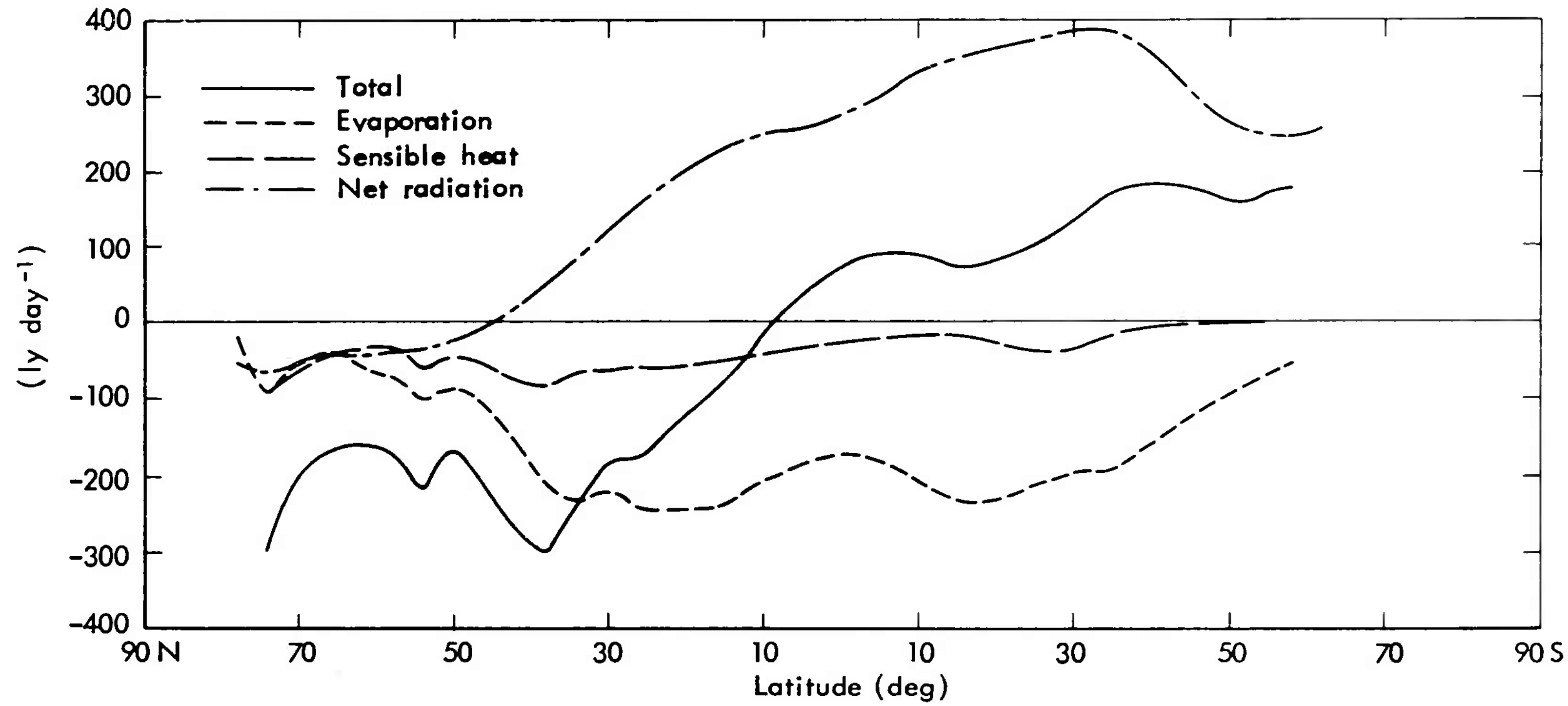

Fig. 20-The zonally averaged heat budget at the earth's surface for the data of Budyko (1963).

largest components of both downward and upward heat transfer. The net surface flux in the Mintz-Arakawa model is larger than that found in either of the other studies and accordingly yields greater radiative warming at the earth's surface. In addition, whereas in the other two figures there is a loss of heat at the surface at all latitudes due to sensible heat, in the Mintz-Arakawa model at certain latitudes some amount of warming occurs. These apparent overestimations of heating are to some extent balanced by the fact that the Mintz-Arakawa model also has the largest values of surface heat loss due to evaporation. The net surface heat budget over the entire globe is small in all three cases, but the zonal structure is such that the Mintz-Arakawa model has larger negative values in the mid-northern latitudes and larger positive values in mid-southern latitudes, with a steeper north-south gradient.

The heat balance of an earth-atmosphere column as represented in Fig. 21a can be expressed (in the notation of Newell et al., 1969) as

$$RN_{EA} = (E - P) + (S_0 + S_L + S_A) + \mathrm{Div}\,(\vec{F}_A + \vec{F}_0) \qquad (1)$$

where RN_{EA} = net radiation across upper surface

E = heat lost by ground surface due to latent heat of evaporation

P = heat gained by atmosphere due to latent heat of condensation (precipitation)

S_0, S_L, S_A = heat stored in ocean, land, and atmosphere, respectively (as temperature changes)

$\vec{F}_A$, $\vec{F}_0$ = vertically integrated (two-dimensional) horizontal heat flux in the atmosphere and ocean, respectively, in cal cm^{-1} day^{-1} (see Fig. 21b)

The heat balance for the atmospheric column alone is

$$(RN_{EA} - R_s) + SH + P = S_A + \mathrm{Div}\,\vec{F}_A \qquad (2)$$

where R_s = net radiation downward across the lower surface

SH = sensible heat gained by the atmosphere from the lower surface

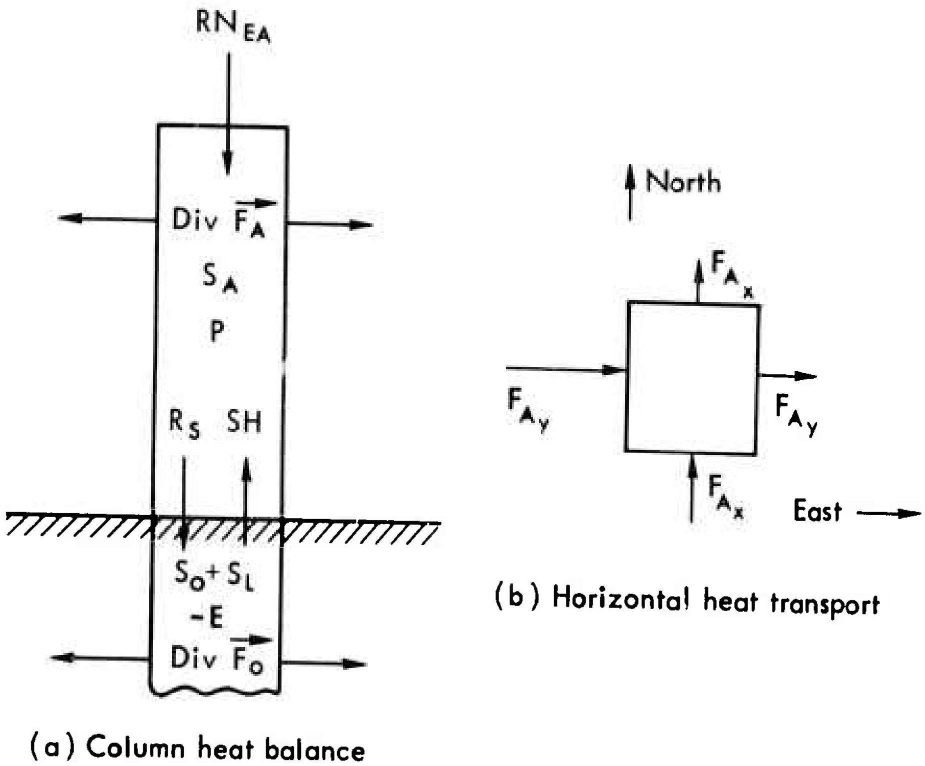

Fig. 21-Schematic representation of the heat balance for an earth-atmosphere column.

In the Mintz-Arakawa model all the quantities appearing in these equations are known except $\vec{F_A}$, $\vec{F_0}$, and S_0. The sum S_0 + Div $\vec{F_0}$ can be found from $S_0 + S_L + \text{Div}\,\vec{F_0} = R_s - SH - E$, with S_L defined to be equal to zero. Either of these equations can then be solved to find Div $\vec{F_A}$.

The zonally averaged January heat budget terms for the atmospheric column are shown in Figs. 22, 23, and 24 for the Mintz-Arakawa model, the GFDL model, and a composite of Möller's (1951) condensation data, Budyko's (1963) sensible heat data, and London's (1957) and Sasamori et al.'s (1972) radiation data. Rather than plot the radiation terms as given in Eq. (2), we have plotted the distributions of solar radiation absorbed by the atmospheric column and net long-wave radiation lost by the atmospheric column. Also, the atmospheric storage and horizontal energy flux terms, S_A and Div $\vec{F_A}$, have been combined to form a single term called the total or imbalance term. This was necessary because the separate terms were only available for the Mintz-Arakawa

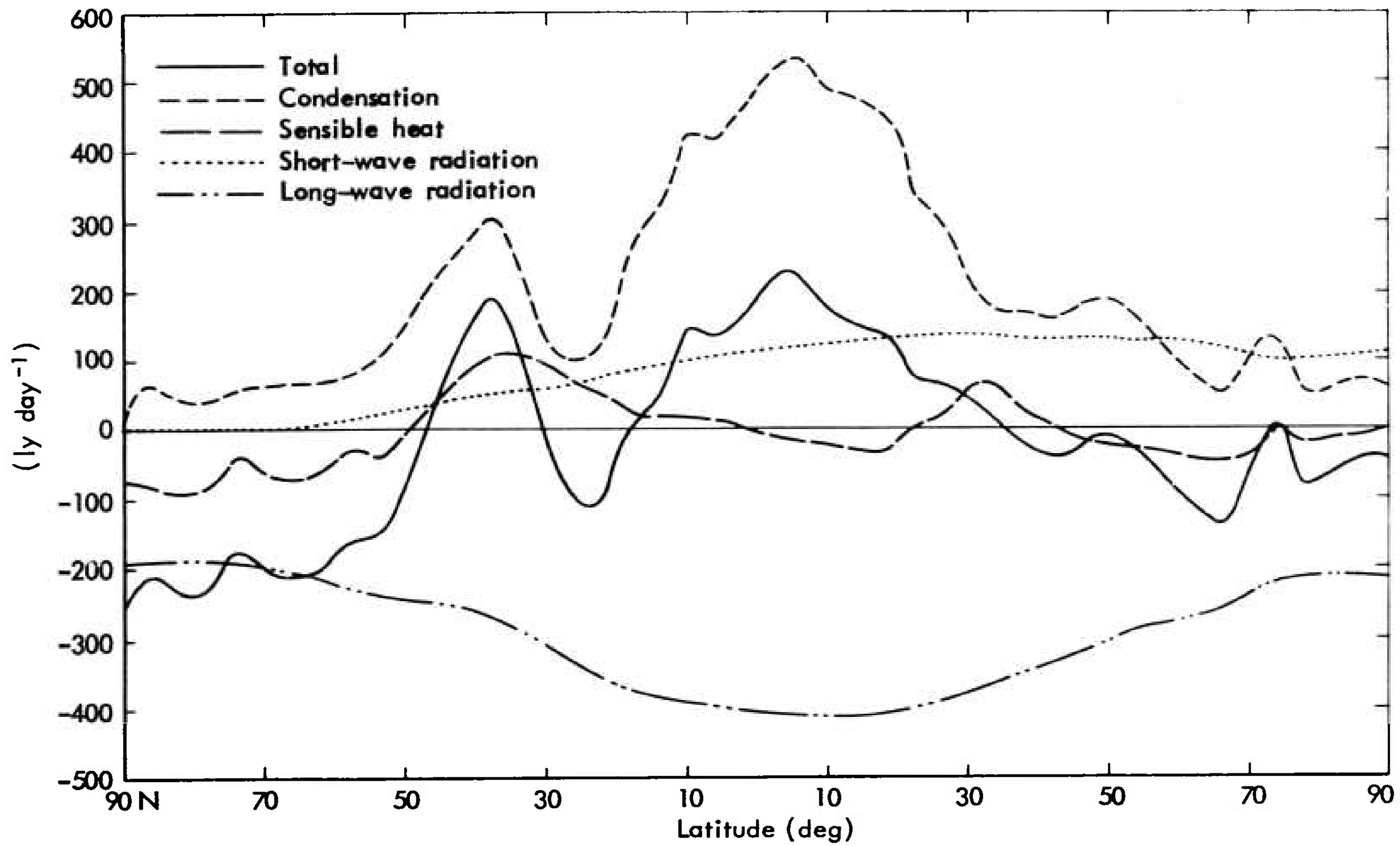

Fig. 22-The zonally averaged heat budget of an atmospheric column for the Mintz-Arakawa model.

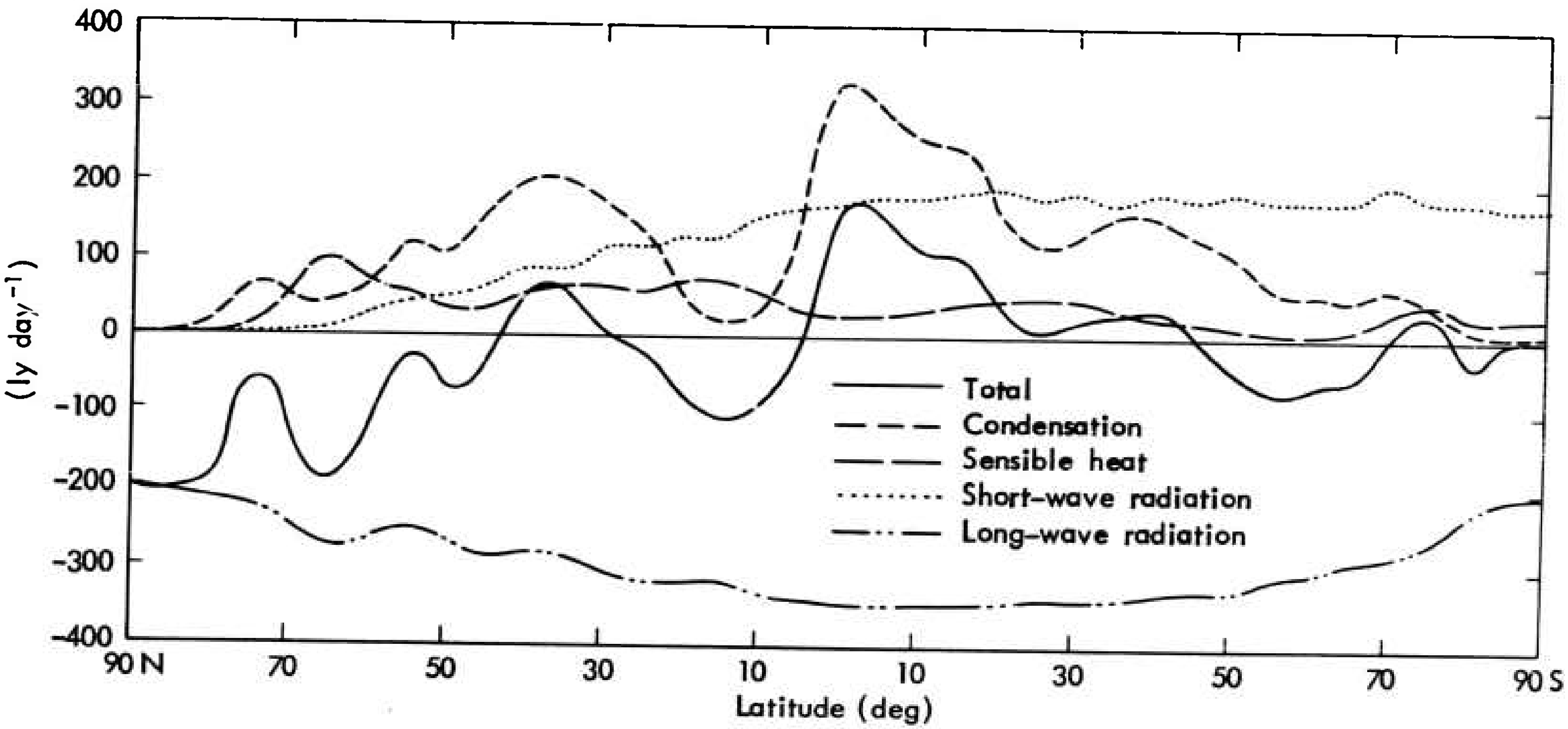

Fig. 23-The zonally averaged heat budget of an atmospheric column for the GFDL model discussed by Holloway and Manabe (1971).

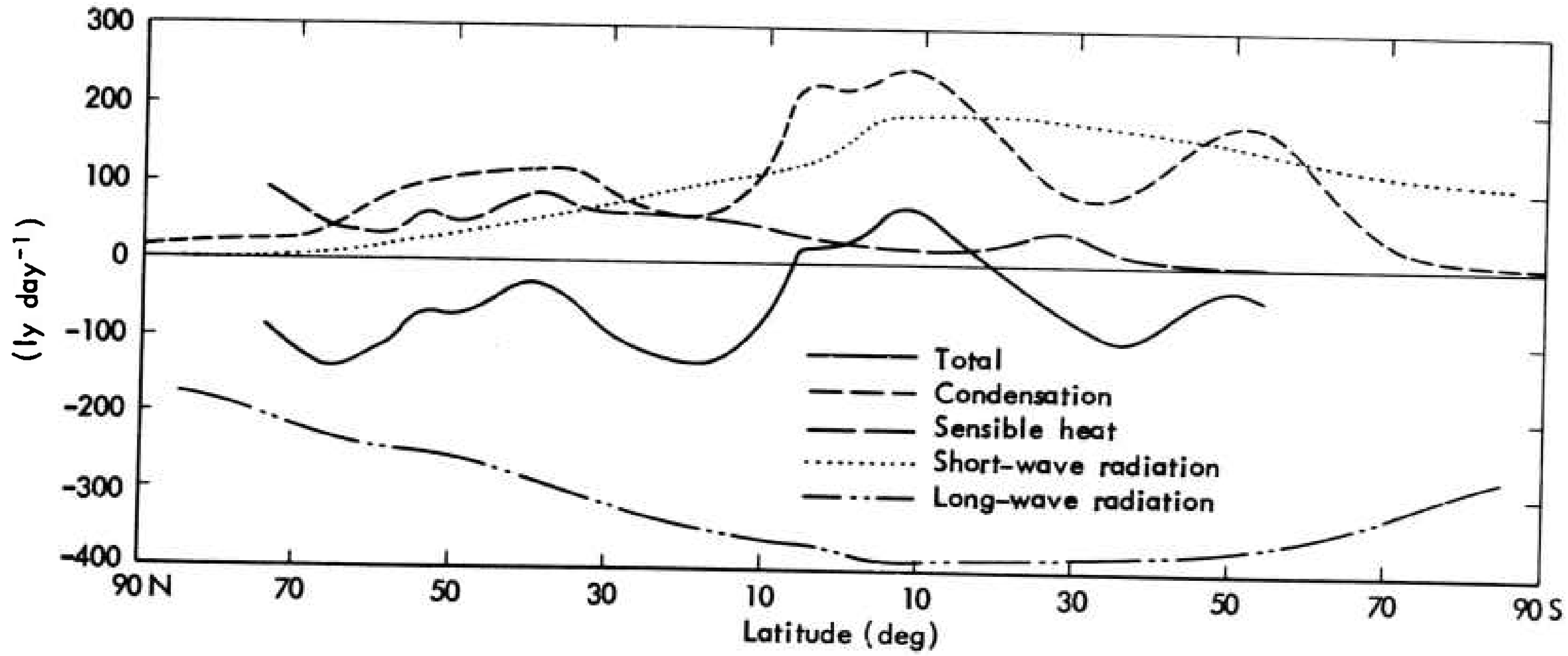

Fig. 24-The zonally averaged heat budget of an atmospheric column for a composite of data.

model. Also, this makes it possible to compare our results with those of Fig. 6 of Newell et al. (1969), who similarly treats the two terms together, and Fig. 35 of Sellers (1965), who considers mean annual values and assumes that the storage term is therefore zero. Values for the atmospheric heat storage, S_A, as calculated by the Mintz-Arakawa model are given in the Appendix, where it can be seen that S_A comprises only a small fraction of the imbalance term, the remainder, Div $\vec{F}_A$, representing the heat which must be transported meridionally by the atmosphere to effect a balance.

In comparing these five figures (Figs. 22, 23, 24 plus Fig. 6 of Newell et al. (1969) and Fig. 35 of Sellers (1965)) several features may be noted. Perhaps most striking is the similarity of the shapes of the condensation and imbalance curves in each figure (ΔC in Sellers' figure). This is, of course, because all the other components vary much more slowly with latitude, but it helps to emphasize the importance of latent heat in the energy-transfer process.

The imbalance or total term in Fig. 24 and from Newell et al. (1969), both representing values derived from a mixture of observed and theoretical data, do not appear to be realistic. They both indicate that the imbalance is predominantly negative, which is physically impossible. When globally averaged the imbalance should go to zero except for the small storage term. Newell et al. have suggested that possible errors in the precipitation, RN_{EA}, or sensible heat* could be involved. The general circulation models, presented in Figs. 22 and 23, are, on the other hand, constructed to conserve energy and therefore should not have this problem. It may be noted, however, that the Mintz-Arakawa model does not have an exact energy balance due to a combination of factors, to be discussed later.

On comparing the atmospheric heat budget of the Mintz-Arakawa model with the other heat budgets, we note, as before, that the Mintz-Arakawa values for most of the components are the largest, both positive and negative, implying a more vigorous general circulation.

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*Newell et al. (1969) speak of boundary flux, which we assume is the sensible heat flux.

Figures 25 and 26 show the various components making up the heat budget for the whole earth-atmosphere system for the Mintz-Arakawa model and from tables of data from Newell et al. (1969) for December, January, and February. In the Mintz-Arakawa model, with its fixed-temperature infinite-heat-capacity ocean, it is not possible to compute S_0 or Div $\vec{F}_0$ separately, but only their sum. To complete Fig. 25, therefore, we have adopted the values of S_0 given by Newell et al. in order to calculate Div $\vec{F}_0$ for the Mintz-Arakawa model. The imbalance term in these figures is Div $(\vec{F}_A + \vec{F}_0)$, the divergence of heat transported by the ocean and atmosphere. Since, as already noted, the atmospheric heat storage term, S_A, is quite small, it has not been plotted in Figs. 25 and 26. There is fairly good agreement between the figures. The larger positive values of the imbalance term in the high southern latitudes in the Mintz-Arakawa model are due to the overly high net radiation in that region, as already noted. The larger negative values in the middle northern latitudes are due to the differences in the precipitation patterns.

The horizontal flux of heat in the ocean and atmosphere was calculated by numerically integrating the zonal averages of Div $(\vec{F}_0 + \vec{F}_A)$ with the appropriate area weighting. This was done for the Mintz-Arakawa model by starting at the south pole and integrating northward, in the manner described by Newell et al. (1969). They, however, redistributed the slight residual at the north pole among the largest flux values, while we did not. The result for the Mintz-Arakawa model and Newell et al. are shown in Fig. 27. Fairly good agreement exists, with the Mintz-Arakawa model requiring a larger horizontal flux in the southern hemisphere and a considerably smaller flux in the northern hemisphere than that indicated by Newell et al.

Finally, we will consider the global averages of the energy balance. From Eqs. (1) and (2), we have

$$RN_{EA} = (E - P) + S_0 + S_L + S_A + \text{Div } (\vec{F}_A + \vec{F}_0) \tag{1'}$$

$$4 = 260 - 258 - 1 + 0 + 5 + (23 - 25)$$

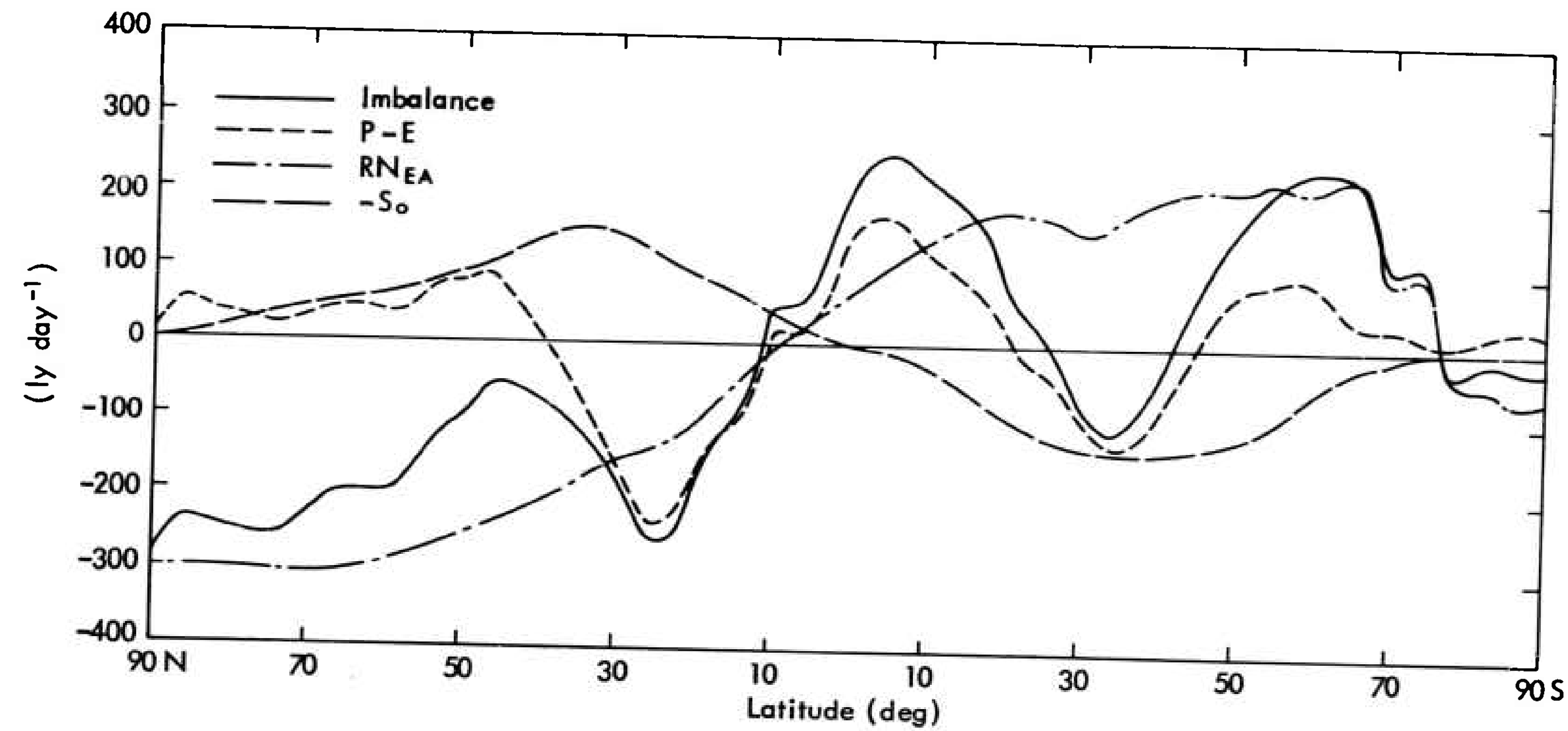

Fig. 25-The zonally averaged heat budget for the earth-atmosphere system for the Mintz-Arakawa model.

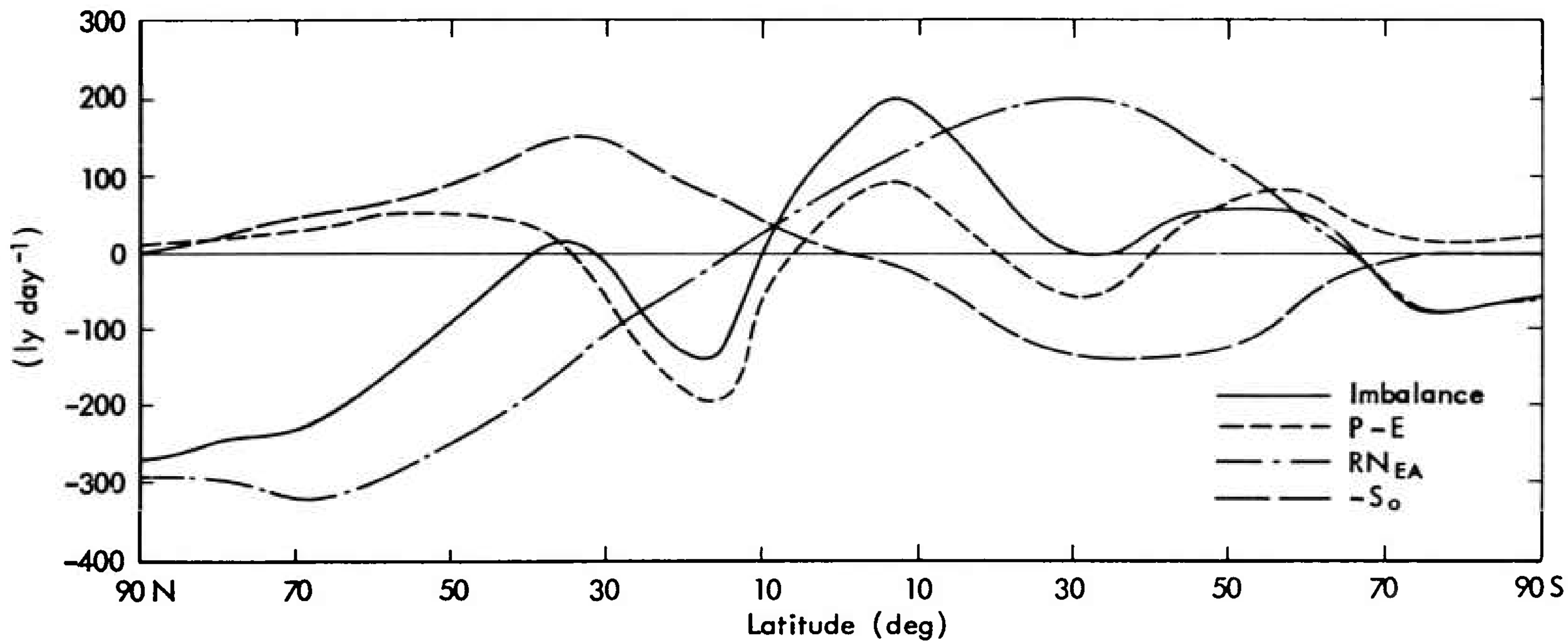

Fig. 26-The zonally averaged heat budget for the earth-atmosphere system for the model described by Newall et al. (1969).

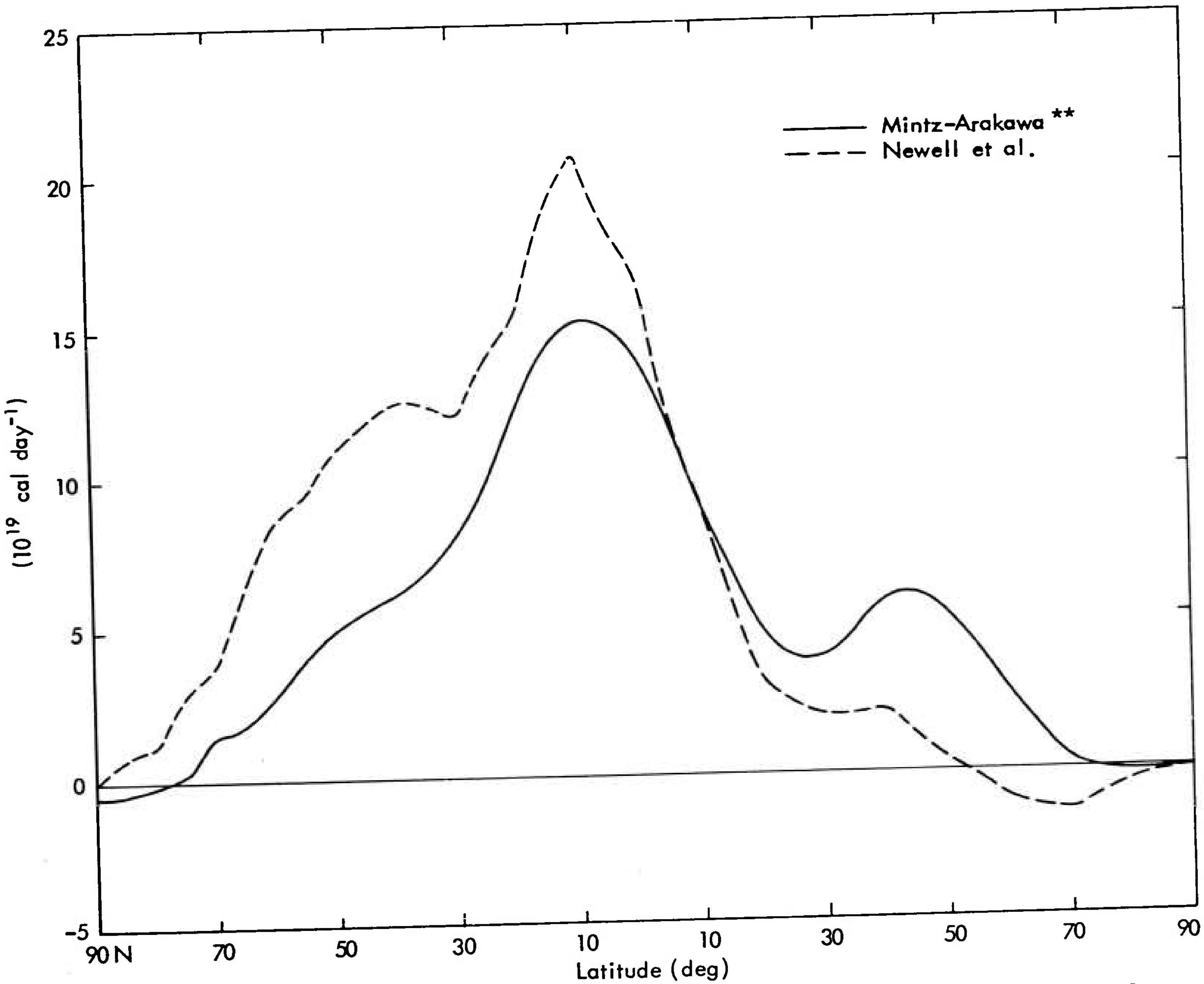

Fig. 27-The horizontal transport of heat in the ocean and atmosphere as derived from the imbalance calculation.

with the numerical values of the global averages of the heat budgets in ly day^{-1}. Similarly,

$$RN_{EA} - R_s + SH + P = S_A + \mathrm{Div}\,\vec{F}_A$$

$$4 - 242 + 8 + 258 = 5 + 23 \qquad (2')$$

Equations (1') and (2') indicate that there is a net 4 ly day^{-1} entering the atmosphere across the upper boundary (RN_{EA}), and 24 ly day^{-1} across the lower boundary ($-R_s + SH + P$). Of the total of 28 ly day^{-1}, only 5 ly day^{-1} are stored in the atmosphere as heat. The other 23 ly day^{-1} are unaccounted for, and since Eq. (2') forces the atmospheric system to be in balance, these 23 ly day^{-1} appear in the horizontal atmospheric heat-transfer term, which should vanish globally. At the present time, however, frictional heating of the earth's surface is not included in the model, and it would appear that if this surface heating is introduced, part of the missing heat will be accounted for. In addition, the use of single precision arithmetic may contribute to the imbalance. Finally, some of the heat energy may be converted into other forms of energy. The net global horizontal transport of heat in the oceans also should be zero. Since the sum of the terms in Eq. (1'), excluding the divergence, is quite small, the non-zero value found for $\mathrm{Div}\,\vec{F}_A$ forces $\mathrm{Div}\,\vec{F}_0$ to be nonzero if the equation is to be balanced. It may be noted that this global average error is 3 percent of the incident solar radiation.

The global heat budget of the Mintz-Arakawa model for January is shown in Fig. 28 and compared, where possible, with London's (1957) values for the mean annual case. The largest differences are in the nonradiative heat transfer occurring across the lower surface. The Mintz-Arakawa model has 35 units of latent heat (where the solar radiation incident on the top of the atmosphere represents 100 units), and 1 unit of sensible heat, while London has 18.5 units of latent heat and 11 units of sensible heat. In addition, London has forced the left-hand side of Eq. (2) to be zero, while the Mintz-Arakawa model has a 3 percent imbalance as noted above, and also a small

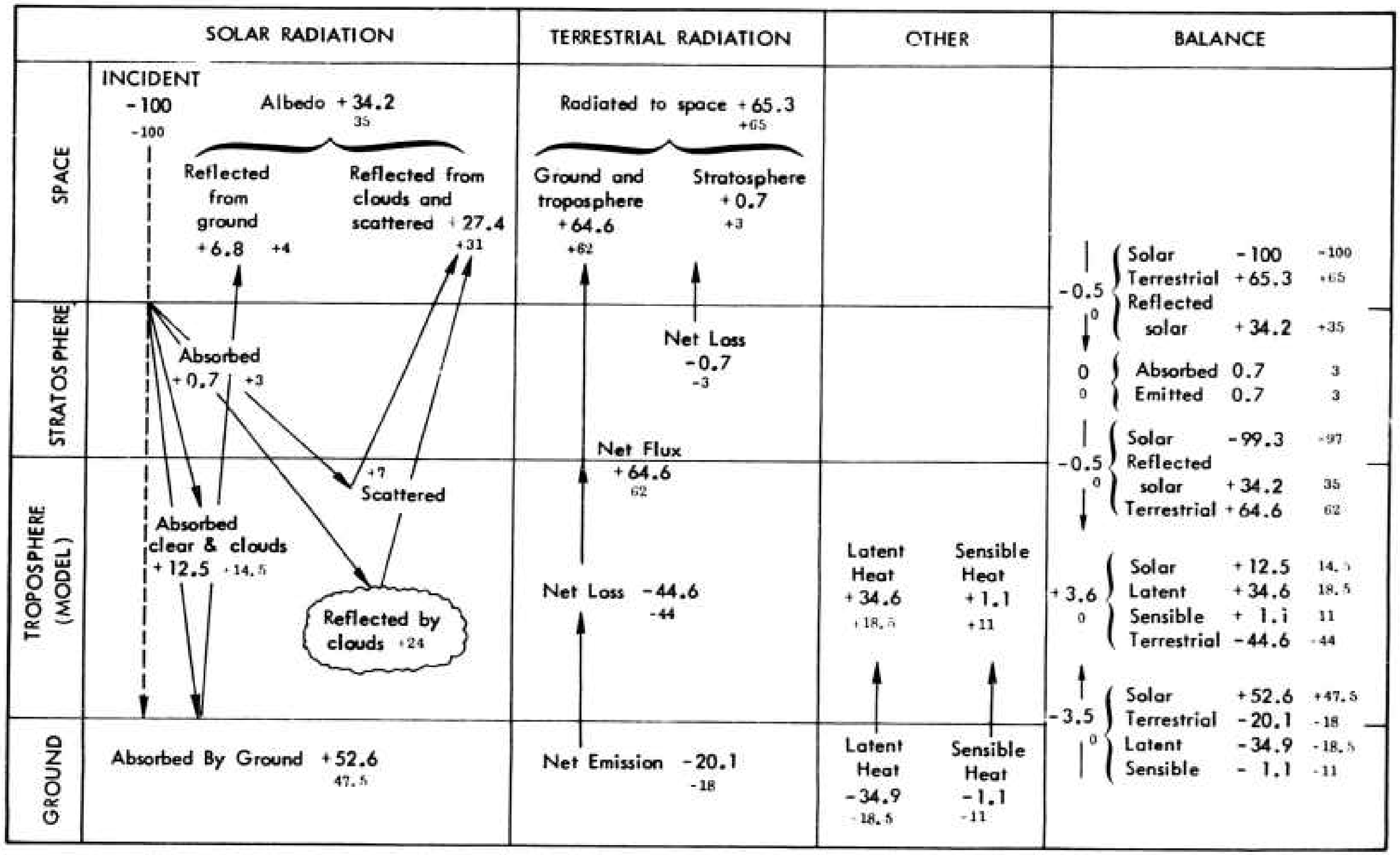

Fig. 28-The global heat budgets from the Mintz-Arakawa model for January (large numbers) and from London's mean annual data (small numbers).

amount of atmospheric heat storage in the form of increases in the evaporated moisture and temperature. Globally, the solar radiation absorbed by the earth's surface in the Mintz-Arakawa model is about 5 units larger (52 units versus 47 units) than in London's results. The long-wave radiation lost to space is approximately the same, while that lost from the earth's surface is slightly larger in the Mintz-Arakawa model.

VI. CONCLUDING REMARKS

In this report we have examined the radiation and heat-budget portions of the Mintz-Arakawa model in order to identify areas not in agreement with the theoretical and observed values available for comparison. In general those features of the model considered here appear to be fairly realistic. In addition, as noted in Sec. V, some of the heat budgets, such as that of Newell et al. (1969), based on a combination of theoretical and observed data, produce unrealistic values for the horizontal heat flux. Therefore, perhaps we should not be too concerned that the various budget terms derived from the Mintz-Arakawa model deviate as they do from the terms in the other budgets. It would also appear that some of the departures can be explained in terms of deficiencies in the moisture and cloud parameterizations of the model, but improvements in this area must await modifications of the model's hydrologic cycle.

There are, however, some areas where the model can be immediately improved. It appears that a slightly lower solar constant is more realistic, and that a representation of ozone absorption is desirable. In addition, dividing the solar spectrum at a wavelength other than 0.9 μ, as discussed in Sec. III, may improve the atmospheric absorption. Adoption of these modifications should improve the model as far as the solar radiation is concerned. For the long-wave radiation of the model, the adoption of the more accurate fit to the Yamamoto radiation chart as developed at UCLA should prove advantageous.* We also hope to ex amine the radiation in the model by using observed climatological parameters rather than those generated by the model, in order to determine whether or not the observed discrepancies are due to the hydrological parameters used in the model, as has been suggested here.

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*M. E. Schlesinger, private communication.

Appendix

NUMERICAL VALUES FROM THE MINTZ-ARAKAWA MODEL

Zonal and global averages of the quantities below, as generated by the Mintz-Arakawa model in a January simulation, are tabulated on the following pages.

Table Notation	Quantity	Units
CL	Cloudiness	fractional
W.V.	Precipitable water vapor	gm cm^{-2}
S. Alb.	Surface albedo	fractional
T_g	Ground temperature	°C
E	Evaporation from surface	mm day^{-1}
P	Precipitation	mm day^{-1}
S_o	Solar radiation, top of atmosphere	ly day^{-1}
S_o - Abs. S.	Solar radiation reaching troposphere	ly day^{-1}
Abs. S.	Solar radiation absorbed in stratosphere	ly day^{-1}
Refl.	Total reflected solar radiation	ly day^{-1}
Abs. T.	Solar radiation absorbed in troposphere	ly day^{-1}
S_4	Solar radiation reaching ground	ly day^{-1}
S_g	Solar radiation absorbed by ground	ly day^{-1}
P. Alb.	Planetary albedo	fractional
R_0	Net long-wave radiation, tropopause (positive upward)	ly day^{-1}
R_4	Net long-wave radiation, ground surface (positive upward)	ly day^{-1}
$R_0 - R_4$	Long-wave flux divergence	ly day^{-1}
RN_{EA}	Net radiation, tropopause (positive downward)	ly day^{-1}
R_s	Net radiation, ground (positive downward)	ly day^{-1}
E(heat)	Latent heat loss from evaporation	ly day^{-1}
P(heat)	Latent heat gain from precipitation	ly day^{-1}
SH	Sensible heat (positive upward)	ly day^{-1}
S_A	Heat storage, atmosphere	ly day^{-1}
Div $\vec{F}_A$	Atmospheric horizontal heat-flux divergence	ly day^{-1}
S_0 + Div $\vec{F}_0$	Heat transferred to ocean	ly day^{-1}
S_0	Heat storage, ocean (from Newell et al.)	ly day^{-1}
Div $\vec{F}_0$	Oceanic horizontal heat-flux divergence	ly day^{-1}

ZONAL, HEMISPHERIC (NH, SH), AND GLOBAL AVERAGES FROM MINTZ-ARAKAWA MODEL

Lat.	CL	W.V.	S. Alb.	T_g	E	P	S_o	S_o-Abs. S.	Abs. S.
90N	.355	.22	.800	-21.7	-.03	.12	0	0	0
86N	.344	.19	.800	-23.2	.11	1.07	0	0	0
82N	.308	.19	.794	-23.9	.08	.75	0	0	0
78N	.331	.21	.753	-22.3	.22	.74	0	0	0
74N	.430	.28	.682	-18.5	.66	.96	0	0	0
70N	.404	.33	.641	-18.8	.51	1.05	1	0	0
66N	.438	.39	.516	-18.3	.35	1.15	16	16	0
62N	.464	.46	.440	-15.2	.42	1.17	55	54	1
58N	.532	.57	.344	-10.5	.72	1.38	105	104	1
54N	.542	.64	.305	-8.4	.59	1.78	159	157	2
50N	.585	.72	.297	-5.1	1.16	2.56	216	214	2
46N	.571	.81	.258	-1.4	2.17	3.71	276	274	2
42N	.532	.91	.153	2.7	3.87	4.51	336	333	3
38N	.483	1.05	.128	6.3	5.52	5.25	396	393	3
34N	.440	1.26	.118	9.9	5.70	4.10	456	452	4
30N	.353	1.41	.122	13.5	5.16	2.28	514	510	4
26N	.331	1.59	.120	18.0	5.73	1.72	572	568	4
22N	.323	1.89	.121	21.3	5.90	2.18	627	622	5
18N	.262	1.92	.103	24.1	6.83	4.48	680	675	5
14N	.254	2.12	.090	26.0	7.15	5.48	731	726	5
10N	.250	2.10	.070	26.2	7.04	7.30	779	774	5
6N	.272	2.19	.068	26.5	6.86	7.12	823	817	6
2N	.271	2.32	.066	27.4	6.39	7.91	864	858	6
2S	.275	2.42	.064	27.3	6.04	8.81	902	896	6
6S	.259	2.35	.066	26.6	6.35	9.16	936	930	6
10S	.264	2.35	.066	26.6	6.32	8.39	966	959	7
14S	.248	2.28	.067	25.8	6.56	8.13	992	985	7
18S	.249	2.27	.070	25.4	6.74	7.71	1014	1007	7
22S	.279	2.43	.083	26.4	6.19	5.91	1032	1025	7
26S	.340	2.43	.079	25.7	5.89	5.17	1046	1039	7
30S	.458	2.47	.078	23.8	5.50	3.82	1055	1048	7
34S	.494	2.21	.065	21.1	5.32	3.00	1061	1054	7
38S	.492	1.87	.063	17.5	4.95	2.92	1062	1055	7
42S	.474	1.62	.075	14.0	3.62	2.78	1060	1053	7
46S	.507	1.49	.073	10.7	2.78	3.06	1054	1047	7
50S	.542	1.34	.073	7.8	1.97	3.22	1045	1038	7
54S	.534	1.14	.081	5.2	1.29	2.75	1034	1027	7
58S	.576	1.09	.080	3.0	.42	2.02	1022	1015	7
62S	.507	1.00	.120	1.0	.17	1.36	1011	1004	7
66S	.431	.86	.160	-0.5	.36	.89	1004	997	7
70S	.358	.60	.450	-2.5	1.33	1.83	1017	1009	8
74S	.352	.40	.450	-4.1	1.93	2.22	1040	1032	8
78S	.441	.33	.732	-9.3	.74	.89	1058	1050	8
82S	.511	.27	.756	-10.4	.71	1.05	1071	1063	8
86S	.632	.20	.800	-11.8	.76	1.26	1079	1070	9
90S	.642	.22	.800	-11.2	.58	1.03	1082	1073	9
NH	.383	1.38	.203	9.8	4.49	3.92	474	470	4
SH	.387	1.88	.112	17.5	4.46	4.97	1016	1009	7
Global	.385	1.63	.158	13.6	4.48	4.45	745	740	5

ZONAL, HEMISPHERIC (NH, SH), AND GLOBAL AVERAGES FROM MINTZ-ARAKAWA MODEL

Lat.	Refl.	Abs. T.	S_4	S_8	P. Alb.	R_0	R_4	$R_0 - R_4$	RN_{EA}
90N	0	0	0	0	0	303	108	195	-304
86N	0	0	0	0	0	300	110	190	-301
82N	0	0	0	0	0	300	112	188	-301
78N	0	0	0	0	0	302	113	189	-303
74N	0	0	0	0	0	305	112	193	-306
70N	0	0	0	0	.087	307	108	198	-307
66N	10	2	8	4	.617	307	101	207	-303
62N	32	7	28	15	.582	317	101	217	-296
58N	59	14	48	30	.563	329	101	228	-286
54N	88	21	70	48	.555	339	100	239	-271
50N	121	29	92	64	.562	348	104	245	-257
46N	149	37	120	88	.540	365	115	249	-242
42N	162	44	150	127	.483	389	132	258	-220
38N	177	50	189	166	.447	416	147	269	-202
34N	183	55	242	214	.401	448	159	289	-181
30N	181	60	306	269	.353	486	179	307	-158
26N	192	67	352	308	.337	522	190	332	-148
22N	206	76	388	340	.328	544	188	356	-127
18N	196	85	441	395	.288	565	192	372	-85
14N	201	93	472	431	.275	574	191	383	-50
10N	205	98	504	470	.264	578	190	388	-9
6N	220	104	528	493	.267	579	184	395	19
2N	227	111	556	520	.263	580	176	404	52
2S	238	117	578	540	.264	577	171	406	82
6S	247	121	602	562	.263	575	165	409	108
10S	252	125	625	583	.261	575	163	413	133
14S	257	127	647	601	.259	573	161	411	157
18S	265	130	662	613	.261	570	161	408	175
22S	285	134	665	606	.276	568	169	399	173
26S	314	136	643	589	.300	556	166	389	170
30S	370	138	593	540	.351	532	155	377	148
34S	384	137	574	533	.361	509	148	362	164
38S	384	134	576	537	.362	486	135	351	187
42S	384	132	581	537	.363	465	129	336	204
46S	398	133	560	516	.378	439	117	322	212
50S	416	132	530	490	.398	414	108	306	210
54S	413	128	531	485	.400	396	107	289	221
58S	433	130	494	452	.423	375	95	281	210
62S	416	125	529	462	.412	372	99	273	218
66S	403	118	569	476	.401	371	110	261	226
70S	548	108	644	353	.538	372	133	239	91
74S	566	99	672	367	.545	370	150	221	98
78S	752	103	734	194	.711	341	125	216	-42
82S	780	104	733	179	.728	332	119	213	-48
86S	822	109	701	139	.762	319	107	213	-70
90S	822	11[illegible]	697	138	.760	319	105	214	-67
NH	157	59	285	255	.363	464	155	309	-150
SH	353	127	601	528	.345	499	144	355	158
Global	255	93	443	392	.354	481	150	332	4

ZONAL, HEMISPHERIC (NH, SH), AND GLOBAL AVERAGES FROM MINTZ-ARAKAWA MODEL

Lat.	R_s	E(heat)	P(heat)	SH	S_A	Div $\vec{F}_A$	S_O + Div $\vec{F}_O$	$-S_O$	Div $\vec{F}_O$
90N	-108	-2	7	-75	-2	-261	-31	0	-31
86N	-110	6	62	-84	1	-213	-32	9	-23
82N	-112	4	43	-93	2	-238	-25	16	-9
78N	-113	13	43	-83	12	-241	-44	30	-14
74N	-112	38	56	-40	11	-188	-111	40	-71
70N	-108	30	61	-64	2	-202	-74	45	-29
66N	-97	20	67	-72	-1	-208	-46	53	7
62N	-86	24	68	-62	6	-210	-48	59	11
58N	-71	42	80	-30	13	-177	-82	67	-15
54N	-52	34	103	-41	14	-169	-45	78	33
50N	-40	68	149	-8	17	-91	-99	90	-9
46N	-27	126	215	31	19	15	-185	105	-80
42N	-5	224	261	76	20	104	-305	125	-180
38N	19	320	304	106	14	178	-408	142	-266
34N	55	331	238	111	7	108	-387	150	-237
30N	90	299	132	95	1	-20	-304	145	-159
26N	118	332	100	68	2	-100	-282	128	-154
22N	152	342	126	50	2	-106	-240	100	-140
18N	203	396	260	27	3	-4	-221	80	-141
14N	240	415	318	19	4	43	-194	64	-130
10N	280	409	424	15	4	144	-143	40	-103
6N	309	398	413	13	5	130	-102	24	-78
2N	344	370	459	0	4	162	-27	8	-19
2S	369	350	511	-9	4	208	29	-4	25
6S	397	368	531	-21	5	216	49	-15	34
10S	420	367	487	-24	5	170	78	-30	48
14S	440	380	472	-34	5	149	93	-52	41
18S	452	391	447	-34	5	130	95	-80	15
22S	437	359	343	-2	4	72	80	-108	-28
26S	423	342	300	18	3	62	63	-122	-59
30S	385	319	221	62	2	42	4	-135	-131
34S	385	309	174	63	2	9	14	-140	-126
38S	402	287	170	25	3	-26	90	-140	-50
42S	408	210	161	1	4	-46	195	-139	56
46S	399	161	178	-18	1	-31	256	-132	124
50S	382	114	187	-23	0	-10	290	-125	165
54S	378	75	159	-29	-4	-26	332	-105	227
58S	357	24	117	-37	-6	-64	370	-78	292
62S	363	10	79	-45	1	-114	398	-48	350
66S	366	21	52	-48	3	-142	394	-27	367
70S	220	77	106	-39	-1	-63	183	-15	168
74S	217	112	129	0	-1	8	106	-4	102
78S	69	43	52	-22	-2	-81	48	0	48
82S	60	41	61	-15	-8	-54	34	0	34
86S	32	44	73	-11	-9	-33	0	0	0
90S	33	34	60	0	-8	-34	0	0	0
NH	100	261	227	24	7	-5	-185	82	-103
SH	384	259	288	-7	2	51	133	-80	53
Global	242	260	258	8	5	23	-26	1	-25

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